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THEORETICAL ANALYSIS OF MULTIMODE FIBER STRUCTURES.(U)

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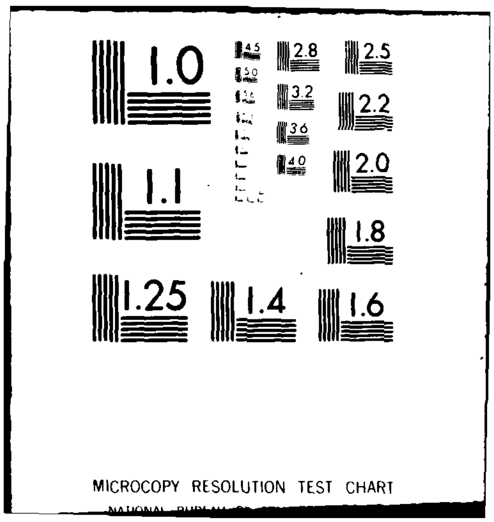
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RADC-TR-80-332
Final Technical Report
October 1980

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THEORETICAL ANALYSIS OF MULTIMODE FIBER STRUCTURES

EMTEC Engineering Incorporated

C. Yeh

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ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, New York 13441

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Some referenced figures do not appear in this document. The references are to computer calculations too voluminous to publish. The resulting analysis of the computer data is adequately presented in this report. Therefore, the missing data is considered irrelevant to the conclusions presented herein. The missing data may be obtained by contacting RADC (ESO) Hanscom AFB MA 01731.

This report has been reviewed and is approved for publication.

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: 18 RADC-TR-80-332	2. GOVT ACCESSION NO.: AD-A093 143	3. RECIPIENT'S CATALOG NUMBER: 9
4. TITLE (and Subtitle): 6 THEORETICAL ANALYSIS OF MULTIMODE FIBER STRUCTURES		5. TYPE OF REPORT & PERIOD COVERED: Final Technical Report, Jan — Aug 80
		6. PERFORMING ORG. REPORT NUMBER: 14 EM-F-02
7. AUTHOR(s): 11 C. Yeh		8. CONTRACT OR GRANT NUMBER(s): 15 F19628-80-C-0053 new
9. PERFORMING ORGANIZATION NAME AND ADDRESS: EMTEC Engineering, Inc. Suite 2032, 1100 Glendon Avenue Los Angeles CA 90024		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 61102F 16 2306J239 17 J2
11. CONTROLLING OFFICE NAME AND ADDRESS: Deputy for Electronic Technology (RADC/ESO) Hanscom AFB MA 01731		12. REPORT DATE: 11 October 1980
		13. NUMBER OF PAGES: 12 103
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Same		15. SECURITY CLASS. (of this report): UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE: N/A

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Same

18. SUPPLEMENTARY NOTES

RADC Project Engineer: Leonard J. Eyges (RADC/ESO)

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Multimode Fiber Waveguides
Multimode Fiber Couplers
Inhomogeneous Dielectric Waveguides

This study examined

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This is a final report on the study of propagation characteristics of a light beam in multimode fiber structures. Realistic fiber structures made with commercially available fibers such as those provided by Corning or ITT were studied. The resultant computer programs may be used readily to generate design data for structures made with realistic fibers with step or parabolic index profiles. It is believed that our unique approach based on the scalar-wave FFT method may be extended to

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treat problems dealing with nonlinear fibers or fibers with frozen-in statistically varying index profiles.

ACKNOWLEDGEMENT

The work reported herein was supported by the Electronic Systems Division of the Air Force Systems Command, USAD, Hanscom AFB. The author wishes to express his special thanks to Dr. L. Eyges for his sincere interest in this project and for his suggestion in the application of our technique to study the large-size single mode fiber. Technical discussion with Dr. P. Gianino was also appreciated. Continuing support of this project by Dr. A Yang is gratefully acknowledged.

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E V A L U A T I O N

The effort as summarized in the report provides accurate theoretical analyses of the optical power transmission properties of a number of devices important to RADC efforts under TPO #4/D - Solid State Devices, Subthrust #3 - Electro-Optical Components. The devices include couplers, tapers, horns, and branches. The programs and techniques provided by the contractor permit in effect computer experiments to be done for a very large variety of design parameters. To do the actual experiments in the laboratory with this range of parameters would be enormously more expensive and time consuming. The report is then a crucial element in simplifying and accelerating the design process and in leading to final design specs in the shortest time.

Leonard Eyges
LEONARD J. EYGES
Project Engineer

I. INTRODUCTION

This final report summarizes the work performed under Contract F19628-80-C-0053 which the Electronic Systems Division of the Air Force Systems Command granted to the EMtec Engineering, Los Angeles, California. The work was begun in January, 1980 and completed in August, 1980.

The principal thrusts of this R & D study in performing numerical analysis of multimode fiber components were two fold. Firstly, we wish to learn the limitation (and possible improvement) of our numerical scheme[1] and secondly, we wish to obtain numerical data for realistic multimode fiber structures. Specifically, the following tasks were carried out:

a) Study the effect of step index gradient and of tight beam confinement by an adaptive coordinate scheme.

b) Study the effect of the presence of absorber at the edge of the mesh on the beam propagation characteristics of multimode fiber structures.

c) Compute the coupling characteristics of tapered multimode fiber couplers and unequal size fiber couplers .

d) Obtain data for reflection coefficients and beam waist changes for multimode fiber tapers, horns and branches.

In section II we shall present the implementation of the adaptive coordinates in our numerical solution of the scalar wave equation. Then, the scheme to include an absorber at the edge of the mesh will be described. Finally, an approximate approach to obtain the reflection coefficients for complex fiber structures will be shown. Detailed results of our study on the proposed tasks are given in Section III. Concluding remarks and recommendations for future work are included in Section IV.

II. ANALYTICAL APPROACH

The basic approach taken to find the solution of wave propagation along complex fiber structures is to solve the reduced scalar wave equation via the fast Fourier transform (FFT) technique.[2] In this section we shall first indicate the conditions underwhich the exact vector wave equation may be simplified to yield the reduced scalar wave equation. Then we shall introduce the concept of adaptive coordinates[3] and incorporate this concept in the solution of the reduced scalar wave equation via the fast Fourier transform technique.

A. Formulation of the Scalar Wave Approach. Starting with the vector wave equation for the electric field vector $\underline{E}$ in the fiber structure,

$$\nabla \times \nabla \times \underline{E} - \omega^2 \mu_0 \epsilon \underline{E} = 0 \qquad (1)$$

where ω is the frequency of the wave, μ_0 the permeability and and $\varepsilon = \epsilon(r)$, the inhomogeneous permittivity of the structure, and making use of the vector identity

$$\nabla \times \nabla \times \underline{E} = \nabla(\nabla \cdot E) - \nabla^2 \underline{E} \qquad (2)$$

and the relation

$$\nabla \cdot \underline{E} = -\frac{1}{\epsilon} \nabla \epsilon \cdot \underline{E} , \qquad (3)$$

one has

$$\nabla^2 \underline{E} + \omega^2 \mu_0 \epsilon \underline{E} - \nabla\left(\frac{1}{\epsilon} \nabla \epsilon \cdot \underline{E}\right) = 0 \qquad (4)$$

Rewriting Eq. (4) gives

$$\nabla^2 \underline{E} + \omega^2 \mu_0 \epsilon_0 \left\{ \frac{\epsilon}{\epsilon_0} \underline{E} - \left[\frac{1}{\omega^2 \mu \epsilon_0} \nabla \left(\frac{1}{\epsilon} \nabla \epsilon \cdot \underline{E} \right) \right] \right\} = 0$$

The relative importance of the terms within the curly brackets can be determined from the following

$$\frac{\epsilon}{\epsilon_0}\,\underline{E} = \mathcal{O}\left(\frac{\epsilon}{\epsilon_0}\,\underline{E}\right) \tag{6}$$

$$\frac{1}{\omega^2\mu\epsilon_0}\,\nabla\left(\frac{1}{\epsilon}\nabla\epsilon\cdot\underline{E}\right) = \frac{1}{k_0^{\,2}}\mathcal{O}\left(\frac{\nabla\epsilon}{\epsilon}\cdot\nabla\underline{E}\right) = \mathcal{O}\left(\frac{\epsilon/\epsilon_0}{k_0\ell}\;\underline{E}\right) \tag{7}$$

where the symbol $\mathcal{O}$ means the "order of magnitude," and ℓ is the smaller of the distance over which ϵ/ϵ_0 and $\underline{E}$ change appreciably. For single-mode fiber structures, the values of ϵ/ϵ_0 and $k_0\lambda$ are typically in the range

$$\epsilon/\epsilon_0 = \mathcal{O}(2) \tag{8}$$

$$k_0\ell = \frac{2\pi}{\lambda}\,\ell = \mathcal{O}\;(10^2 \text{ or } 10^3)\;, \qquad \begin{array}{l}\ell = \mathcal{O}(10\mu \text{ to } 100\;)\\ \lambda = \mathcal{O}(1\mu)\end{array} \tag{9}$$

It follows that the second term within the curly brackets in Eq. (5) is several orders of magnitude smaller than the first term $\epsilon/\epsilon_0\,\underline{E}$. It is therefore justifiable to neglect the second term and write Eq. (5) in the form

$$\nabla^2\underline{E} + k_o^2\,\frac{\varepsilon}{\varepsilon_o}\,\underline{E} = 0$$

The physical significance of replacing Eq. (5) by Eq. (10) is this. By discarding the term $\nabla\frac{1}{\varepsilon}\nabla\varepsilon\;\underline{E}$, we are neglecting any depolarization effects that may occur. This means that the wave retains the polarization it has at the source, which is evidenced by the fact that Eq. (10) can be reduced to a scalar equation by writing $\underline{E}(\underline{x})$ in the form

$$\underline{E}(\underline{x}) = \underline{e}_p u(\underline{x}) \tag{11}$$

where $\underline{e}_p$ is a unit vector in the direction of the initial polarization of the wave.[4] Subsituting Eq. (11) in Eq. (10), we find that u(x) satisfies the scalar wave equation,

$$\nabla^2 u + k_o^2 \frac{\varepsilon}{\varepsilon_o} u = 0 \tag{12}$$

This equation with the boundary condition on the initial surface, and the radiation condition at infinity, completely specifies u(x), from which we can then obtain the electromagnetic field vectors $\underline{E}$ and $\underline{H}$.

If we write u as the product of a factor $e^{ikn_o z}$ that accounts for the rapid change in the phase of u along the direction of propagation and a complex amplitude $A(\underline{x},z)$, a further simplification of the problem results

$$\left[2ikn_o \frac{\partial}{\partial z} + \nabla_T^2 + k^2(n^2(\underline{x},z) - n_0^2)\right] A(\underline{x},z) = -\frac{\partial^2 A(\underline{x},z)}{\partial z^2} \tag{13}$$

where ∇_T^2 is the transverse Laplacian $\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$, and n_0 is a given constant which represents the refractive index of some uniform medium. At laser wavelengths the complex amplitude $A(\underline{x})$ varies much more rapidly transverse to the direction of propagation than it does along the direction of propagation. This enables us to make the paraxial approximation wherein the term on the right side of Eq. (13) is neglected (in the Russian literature this is called the parabolic approximation). So, the complex amplitude now satisfies

$$\left[i2kn_o \frac{\partial}{\partial z} + \frac{\partial}{\partial x^2} + \frac{\partial^2}{\partial y^2} + k^2(n^2(\underline{x},z) - n_o^2\right] A(\underline{x},z) = 0 \tag{14}$$

For given initial data, i.e., values of the field at points on the initial surface, the propagation simulator must generate the corresponding field values at the terminal aperture such that Eq. (14) is satisfied. To do this we divide the medium into slabs defined by planes on which z is constant. In going from one slab to the next, we write $A(\underline{x},z)$ in the form

$$A(\underline{x},z) = e^{\Gamma(x,z)}\, w(\underline{x},z) \tag{15}$$

where $\Gamma(\underline{x},z)$ is a phase function associated with the medium inhomogeneities

$$\Gamma(\underline{x},z) = \frac{ik}{2}\int_{z_o}^{z}\left[n^2(x,y,z') - n_o^2\right]dz'. \tag{16}$$

The modified complex amplitude $w(\underline{x},z)$ then satisfies the equation

$$\left[i2kn_o\frac{\partial}{\partial z} + e^{-\Gamma}\,\nabla_T^2\, e^{\Gamma}\right] w(\underline{x},z) = 0 \tag{17}$$

with the initial condition

$$w(x,y,0) = u(x,y,0) \tag{18}$$

Physically, these equations approximate the propagation in the inhomogeneous medium by a two-step process at each z increment. First, we propagate the field $u(\underline{x})$ at $z - \Delta z/2$ to $z + \Delta z/2$, assuming that the intervening space is homogeneous. The effect of the inhomogeneities between $z - \Delta z/2$ and $z + \Delta z/2$ is then accounted for by multiplying this solution by the phase factor $\exp(\Gamma)$.

B. Adaptive Coordinates

To reduce the size of the mesh required to solve Eq. (17) numerically,

let us introduce an adaptive coordinate system defined by the transformation[5]

$$\zeta_1 = \frac{x/\rho_o}{N(z)} \tag{19}$$

$$\zeta_2 = \frac{y/\rho_o}{N(z)} \tag{20}$$

$$N(z) = \alpha^{-1/2} \left[\left(1 - \frac{z}{f}\right)^2 + \alpha^2 \left(\frac{z}{k\rho_o^2}\right)^2 \right]^{1/2} \tag{21}$$

$$\xi = \tan^{-1} \left[\frac{(1+\beta)\ \frac{z}{f}}{\beta^{1/2}} - 1 \right] \tag{22}$$

$$\beta^{1/2} = \alpha \frac{f}{k\rho_o^2} \tag{23}$$

where ρ_0 is a characteristic dimension of the beam at the initial surface (e.g., the e-fording radius of a gaussian beam), f is the distance to the focus, and α is a constant determined by the requirement that the solution be confined within the boundaries of the mesh at the focal plane. The choice $\alpha = 1$ yields a coordinate system that converges at a rate determined by the free-space diffraction of a gaussian beam having an e-folding radius ρ_0.

When written in terms of the converging coordinate variables defined above, Eqs. (15) and (17) for the complex amplitude are replaced by the relations

$$w(x,y,z) = \hat{\omega}(\underline{\zeta},\xi)\ \exp(\tilde{\Gamma})\ v(\underline{\zeta},\xi) \tag{24}$$

$$\hat{\omega}(\underline{\zeta},\xi) = \left(\alpha^{1/2}\ N(z)\right)^{-1} \exp\left[\frac{i}{2}\left(\zeta_1^2 + \zeta_2^2\right) \tan\xi\right] \tag{25}$$

$$\tilde{\Gamma} = \frac{ik}{2} \int_{z-\Delta z/2}^{z+\Delta z/2} dz' \left(n^2(x,y,z')-1\right) - \frac{i}{2}\left(\zeta_1^2 + \zeta_2^2\right) \Delta\xi \tag{26}$$

$$\left[\frac{\partial}{\partial\xi} - \frac{i}{2} \exp(-\tilde{\Gamma}) \left(\frac{\partial^2}{\partial\zeta_1^2} + \frac{\partial^2}{\partial\zeta_2^2}\right) \exp(\tilde{\Gamma})\right] v = 0 \tag{27}$$

where $\Delta\xi$ is the increment in ξ in going from $z-\Delta z/2$ to $z+\Delta z/2$. The initial condition for v is

$$v(\underline{\zeta},\xi) = w(x,y,z)/\hat{\omega}(\underline{\zeta},\xi) \tag{28}$$

To solve Eq. (27) we utilize the fact that for sufficiently small values of $\Delta\xi$ (i.e., Δz) the effect of the exponential factors exp $(\pm\tilde{\Gamma})$ in this equation is small. Hence, we solve the simpler equation obtained when these factors are equated to unity

$$\left[\frac{\partial}{\partial\xi} - \frac{i}{2}\left(\frac{\partial^2}{\partial\zeta_1^2} + \frac{\partial^2}{\partial\zeta_2^2}\right)\right] v = 0 \tag{29}$$

We use a fast Fourier transform technique to solve Eq.(29). The basis of this approach is the fact that the solution of Eq. (29) can be expressed in the form of a discrete Fourier series

$$v(\underline{\zeta},\xi) = \sum_{m=0}^{N-1} \sum_{n=0}^{N-1} V_{mn}(\xi,t) \exp\left[i(p_m\zeta_1+q_n\zeta_2)\right] \tag{30}$$

where the Fourier coefficients V_{mn} are determined from the initial data and Eq. (29) as follows. The initial values of V_{mn} are obtained by taking the discrete Fourier transform of the initial values of $v(\underline{\zeta},\xi_i)$ over a mesh of points $\zeta_1 = [\ell-(N/2)]\,\Delta\zeta$, $\zeta_2 = [j-(N/2)]\,\Delta\zeta$ $(\ell,j = 0,1,\dots,N-1)$

$$V_{mn}(\xi_i) = \frac{(-1)^{m+n}}{N^2} \sum_{\ell=0}^{N-1} \sum_{j=0}^{N-1} v\left(\left(\ell - \frac{N}{2}\right)\Delta\zeta,\ \left(j - \frac{N}{2}\right)\Delta\zeta, \xi_i\right)$$

$$\exp\left[-\frac{i2\pi}{N}(m\ell + nj)\right] \tag{31}$$

The dependence of V_{mn} is then determined by subsituting Eq. (30) in Eq. (31), which yields

$$\frac{\partial V_{mn}}{\partial \xi} + \frac{i}{2}\left(p_m^2 + q_n^2\right) V_{mn} = 0 \tag{32}$$

from which it follows that

$$v_{mn}(\xi) = V_{mn}(\xi_i) \quad \exp\left[- \frac{i\left(p_m^2 + q_n^2\right)\Delta\xi}{2}\right] \tag{33}$$

Finally, it can be shown that in order for the discrete Fourier series representation of v given in Eq. (30) to be real when v is real, the coefficients p_m and q_n must have the form

$$p_m = \frac{2\pi}{N\Delta\zeta}\left(m - \frac{N}{2}\right) \tag{34}$$

$$q_n = \frac{2\pi}{N\Delta\zeta}\left(n - \frac{N}{2}\right) \tag{35}$$

Hence, for discrete points $\zeta_1 = (\ell - N/2)\Delta\zeta$, $\zeta_2 = (j - N/2)\Delta\zeta$ $(\ell,\ j = 0,1,\ldots,N-1)$

$$v\left(\left(\ell - \frac{N}{2}\right)\Delta\zeta,\ \left(j - \frac{N}{2}\right)\Delta\zeta,\ \xi\right)$$

$$= (-1)^{\ell+j} \sum_{m=0}^{N-1} \sum_{n=0}^{N-1} (-1)^{m+n}\ V_{mn}(\xi_i)$$

$$\exp\left[- i\ \hat{\beta}\left(\left(\frac{m - \frac{N}{2}}{N}\right)^2 + \left(\frac{n - \frac{N}{2}}{N}\right)^2\right) + i\ \frac{2\pi}{N}\ (\ell m + jn)\right] \tag{36}$$

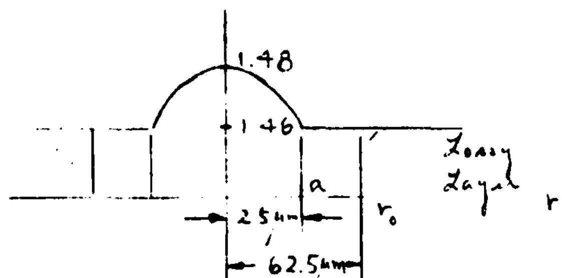
where $\hat{\beta} = 2\pi^2 \Delta\xi/(\Delta\xi)^2$. Note that v is simply $(-1)^{\ell+j}$ times the discrete Fourier transform of $(-1)^{m+n}$ $V_{mn}(\xi)$.

The effect of the medium and the factor $\exp[(-i/2(\zeta_1^2 + \zeta_2^2)\Delta\xi]$ introduced by the coordinate transformation is taken into account at each ξ step in the calculation by multiplying the value of v obtained in the previous step by the quantity $\exp(\tilde{\Gamma})$ defined in Eq. (26), i.e., the initial value inserted in Eq. (31) is $\exp(\tilde{\Gamma})$ times the value of v determined from the previous steps.

Using this adaptive coordinate algorithm we have been successful in our treatment of various realistic multimode fiber structures. Results are summarized in Section III.

C. Implementation of Lossy Outer Boundary.

It is believed that the field touching the outer boundary of the cladding region of a fiber structure will be attenuated due to radiation or absorption. To accomodate this situation in order to further improve our computer simulation, we have incorporated the presence of a lossy dielectric layer outside the cladding region in our computer program. An example of the index profile of a fiber is shown in Fig. 1:



$0 < r < a$	$n = n_a(1-\delta \frac{r^2}{a^2})$,	$a = 25\ \mu m$
$a < r < r_0$	$n = n_a(1-\delta)$,	$r_0 = 62.5\ \mu m$
$r_0 < r$	$n = n_r + in_i$	

Figure 1: A Typical Index Profile with Lossy Outer Layer

Typical intensity patterns of beams propagating in a fiber with the index profile given by Fig. 1 are shown in Fig. 2. It was found that the propagation characteristics of the guided beams are not significantly affected by the presence of a lossy outer layer, except when the spot size of the beam is larger than the core diameter, as expected.

D. A Heuristic Approach in Obtaining the Reflection Coefficient.

One of the a'prior assumption in the development of the FFT scalar wave approach is that only paraxial rays are allowed and no reflection is permitted. This assumption enables us to develop an algorithm, there-by, we may obtain the propagating field by a forward stepping process as described earlier. As the field evolves from one z plane to the next z + Δz plane, the averaged value of the refractive index as seen by the field may be different as illustrated in Fig. 3:

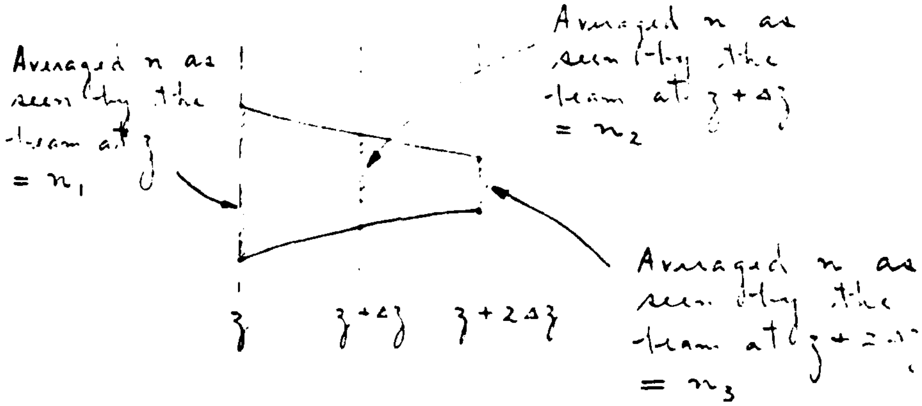
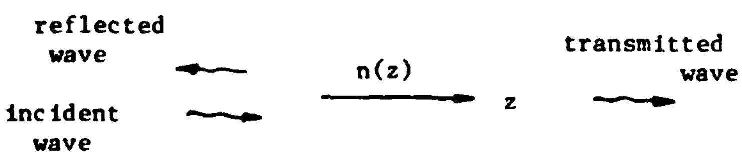


Figure 3: Illustration of the averaged n as seen by the beam.

In affect one may postulate that the wave is experiencing reflection in a medium with longitudinally slowly varying refractive index as shown below:



n(z) is given by Fig. 3.

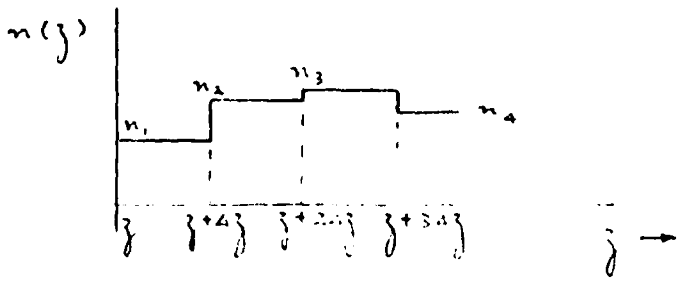


Figure 4: Equivalent Index Profile

The reflection coefficient for a plane wave propagating in this longitudinally non-uniform medium may be obtained according to a formula derived for the case of plane wave propagation in stratified layered medium:[6]

$$R(z) = -\exp[-is(z)] \int_{z}^{-\infty} \gamma(z) \exp[is(z)]\, dz$$

$$s(z) = 2\int^{z} \beta(z)dz \qquad \beta(z) = k_0 n(z)$$

$$\gamma(z) = \frac{\partial\beta}{\partial z} / 2\beta$$

This is the heuristic approach that we shall use to calculate the reflection coefficient for waves in our multimode fiber structures.

III. Results

The algorithms detailed above have been implemented in our computer programs. Results for the proposed tasks are given in the following:

(a) Effects of Step Index Gradient on the Propagation Characteristics.

The purpose of this study is to learn the effects of step index gradient on the propatation characteristics of waves in a multimode fiber guide. Let us introduce the following index profile:

$$n(r) = n_0 - \delta \left(\frac{r}{a}\right)^{2m} \qquad (o<r<a)$$

$$n(r) = n_0 - \delta \qquad (a<r)$$

where n_0, m and δ are given constants and a is the core radius of the fiber. For a typical parabolic index profile fiber, one has

$$n_0 = 1.48, \quad \delta = 0.02, \quad a = 25\mu m, \quad m = 1.$$

The constant δ must necessarily be small so that the depolarization effect may be ignored and the scalar wave approach may be justified. By varying m, the steepness of the index gradient may be varied as shown in Fig. 5. It should be kept in mind that even when the FFT technique is capable of handling steep index variations, the slope of the index profile must still be gentle enough so that the gradient term in the exact wave equation (Eq. (5)) may be ignored. We have carried out propagation calculation for the following specific cases: $n_0 = 1.48$, $\delta = 0.02$, $a = 25\mu m$, $m = 1,4,6,10$. Higher m values means steeper index gradient. As shown in Figs. 6, no computational difficulties were encountered for even the steepest case ($m = 10$) in which the index changes from $n = 1.48$ to $n = 1.46$ in $3\mu m$ distance for $50\mu m$ core diameter fiber. However, one should be aware that we are pushing the limit of validity for the scalar wave approach.

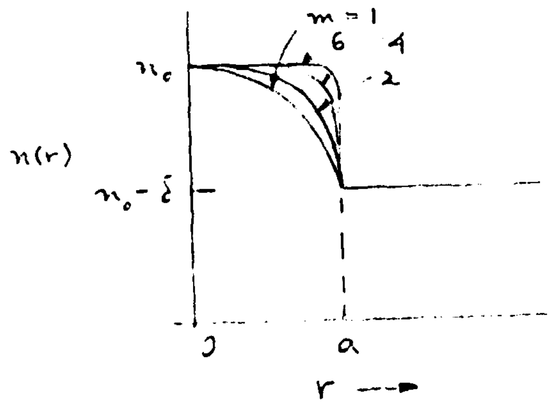


Fig. 5. Plot of $n(r) = n_0 - \delta\,(r/a)^{2m}$.

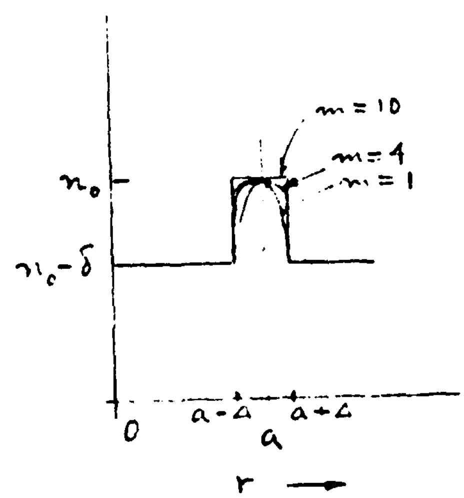


Fig 7 Plot of $n = n_0 - \delta\,((r-a)/\Delta)^{2m}$

From the results, it is of interest to note that as m increases from 1, i.e, as the index profile deviates from the parabolic profile, the beam profiles no longer remain to be of gaussian shapes, but take on ring-type structures. This implies that the phase front of the multimode beam is no longer a monotonic function of the radial distance but has become an oscillatory one.

We may conclude from these calculations that our program is capable of handling problems with steep index gradient. The index transition may occur in a distance as small as 4λ where λ is the free-space wavelength. The limiting factor apparently is the justification for the elimination of the depolarization term in Eq. (5).

(b) Beam Propagation in a Ring Fiber

A typical single-mode fiber has a core diameter of the order of 10μm. Consequently it is more difficult to handle than a multi-mode fiber. An idea to enlarge the single-mode fiber has recently been put forth by Dr. L. Eyges of RADC. He suggested that perhaps a ring-type structure may support a single mode and yet possesses larger dimension than the usual solid-core fiber. This task was undertaken to investigate this possibility. Let us postulate that the index profile of a ring fiber takes the following form

$$n = n_0 - \delta \left(\frac{r-a}{\Delta}\right)^{2m} \qquad \text{for } a-\Delta<r<a+\Delta$$

$$n = n_0 - \delta \qquad \text{for } a-\Delta>r,\ r>a+\Delta$$

where n_0, δ, a, Δ, and m are given constants. By increasing the m value. one may adjust the steepness of the index gradient as shown in Fig. 7. Two types of initial beam shapes will be studied: (1) a solid centered gaussian beam and (2) a hollow-centered donut beam. We wish to learn how well the ring fiber will confine these two types of beams. The field expression for a solid gaussian beam takes the form

$$u = e^{-\frac{\alpha}{2}\left(\frac{r}{a}\right)^2}$$

while the hollow-centered donut beam takes the form

$$u = e^{-\frac{\alpha}{2}\left[\left(\frac{r}{a}\right)^2 - 1\right]}$$

where α and a are given constants. Results of our computation are shown in Figs. 8 and 9. By following the evolution of the beam intensities, one may determine how well the ring fiber is guiding the beam. It can be seen from these figures that the solid beams appear to be better confined than the hollow beams, although the spreading of the solid beam energy is quite noticeable. It also appears that simple insertion of beam energy in the high index region of the ring fiber does not insure good guidance of the beam energy. One may conclude from this preliminary study that neither solid Gaussian beams nor hollow-centered Gaussian beams correspond to the mode energy distribution of a single-mode in a ring fiber. One should first perform the classical modal analysis to obtain the mode pattern of the single mode and then use this mode pattern as the initial beam pattern for propagation down the ring fiber. It is believed that the use of ring-index fiber as large core single-mode fiber definitely possesses merit and should be studied further. What we have demonstrated with our present study is that our program is capable of handling this type of fibers.

(c) Fiber Couplers

One of the simplest type of light couplers is the fiber coupler. By placing two or more fibers in close proximity of each other light energy may transform from one to the other through the coupling effect. This coupling process is rather involved. The well-known coupled mode theory may be adequate for simple, single-mode structures such as slabs

with reasonable separations. But, when multi-mode complex structures such as the fiber couplers are involved, the coupled mode theory becomes grossly inadequate.[7]* On the other hand, our FFT-scalar wave approach is uniquely qualified to deal with this fiber coupler problem. This is because this technique provides the evolution of beam field as it propagates down a complex multimode inhomogeneous fiber structure. Four types of fiber couplers have been studied:

Case 1 Coupling between two equal parabolic index fibers.

Two graded-index fibers are fused together longitudinally with separation d between their centers. The index profile for each fiber is given by

$$n\left(r_{1,2}\right) = n_0 - \delta\left(\frac{r_{1,2}}{a}\right)^2$$

where n_0, δ, and a are given constants, and 1 or 2 refers, respectively, to #1 or #2 fiber. Typical values for a Corning or ITT graded index fibers are used:

$$n_0 = 1.48$$
$$\delta = 0.02$$
$$a = 25\mu m$$

*Recent advances by L. Eyges and P. Gianino of RADC using the extended boundary condition technique have shown that single mode couplers involving arbitrarily shaped uniform core guides can be successfully and accurately treated.

Various separation d were used. A gaussian beam represented by

$$u(x,y) = u_0 \ \exp \left\{ \left[- (x + \frac{d}{2})^2 - y^2 \right] / w^2 \right\}$$

where u(x,y) is the scalar wave function of the beam, and u_0, w are given constants, is incident on one of the fibers. Results have been obtained for

$$w = 2.5\mu m, 5\mu m, 10\mu m$$

$$d = 8\mu m, 12\mu m, 16\mu m, 20\mu m.$$

The evolution of the beam along this structure is shown in Figs. 10-11 Displayed in Figs. 12 is the %-power in one fiber as a function of longitudinal distance for various separations and initial beam sizes. For the situations considered above, many modes are excited. The coupling process is very involved as displayed in Fig. 10-11 It still appears that back and forth power exchange among the guides prevails. The complexity of the power exchange phenomenon for the multimode coupler re-emphasizes the importance of obtaining design data through analysis before the actual construction of fiber coupler.

Case 2 Coupling between two equal step-index fibers.

This coupler is identical to the previous one except step-index fibers were used. We shall approximate the index profile of a step index fiber by the following expression:

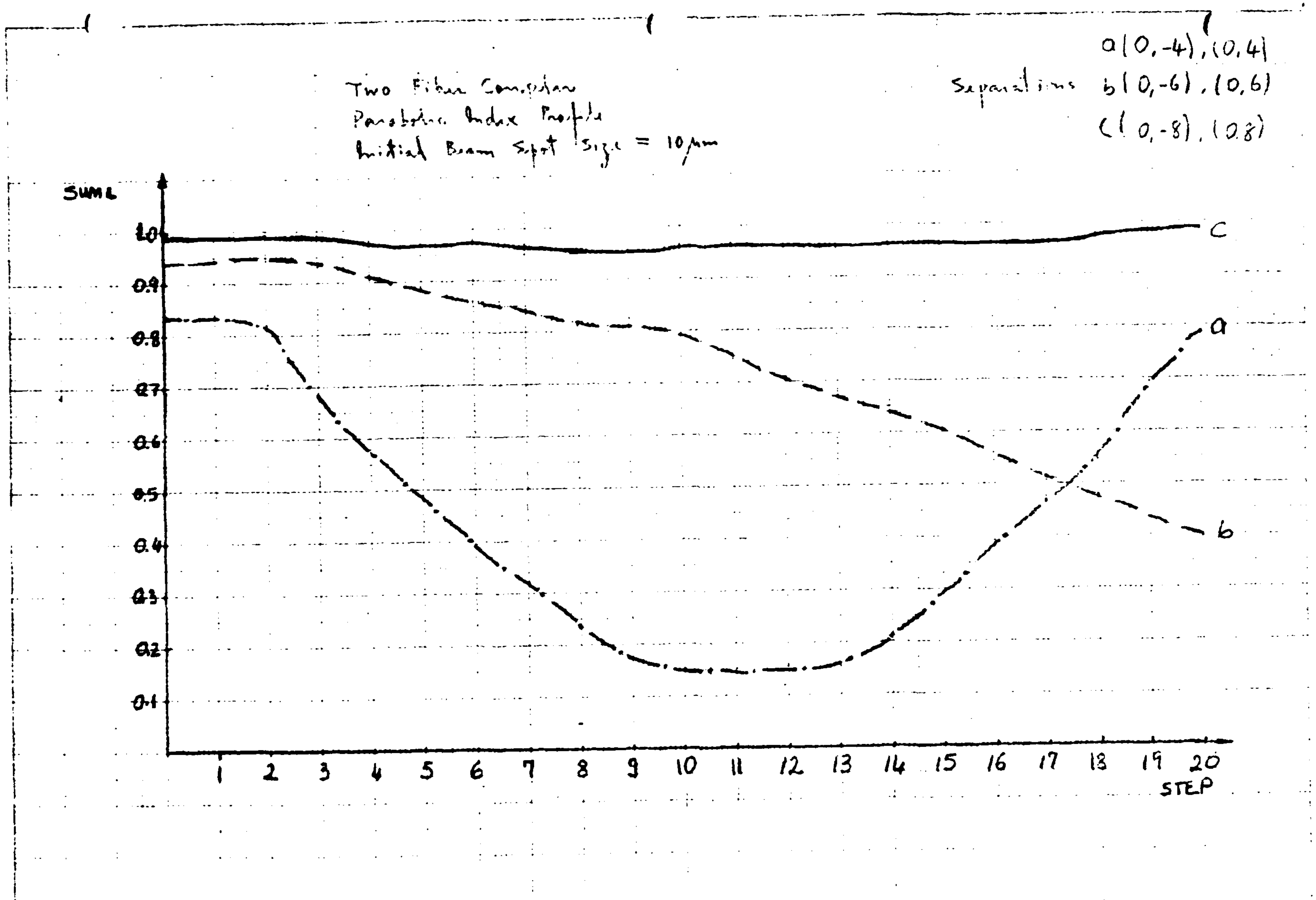

Two Fiber Coupler
Parabolic Index Profile
Initial Beam Spot Size = 10μm
Separations a(0,-4),(0,4)
b(0,-6),(0,6)
c(0,-8),(0,8)
SUML
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
STEP
c
a
b

FIG 12 (a)

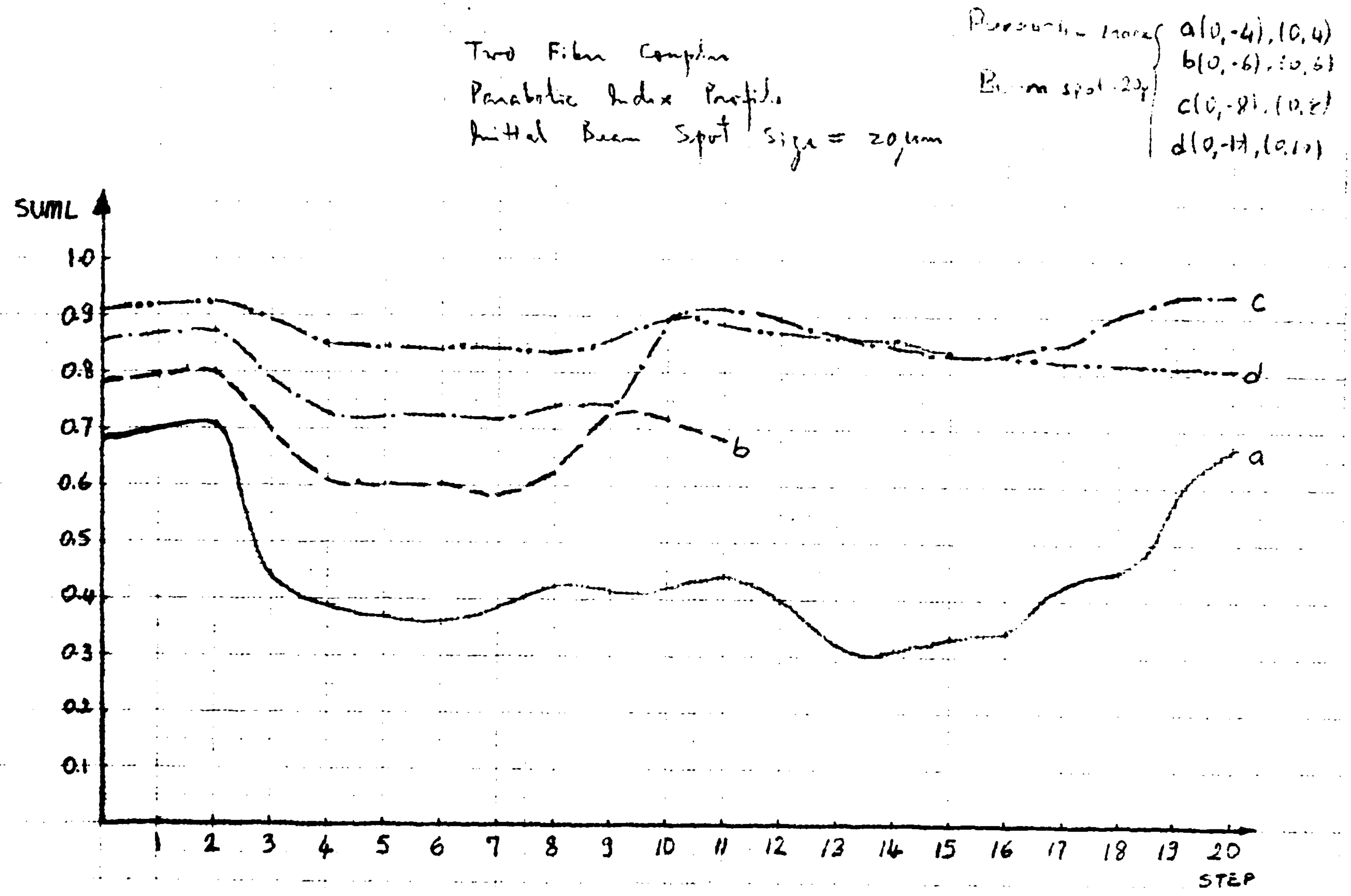

Two Film Coupler
Parabolic Index Profile
Initial Beam Spot Size = 20μm
a(0,-4),(0,4)
b(0,-6),(0,6)
c(0,-8),(0,8)
d(0,-11),(0,11)
SUML
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
STEP
a
b
c
d

FIG 12 (b)

$$n\,(r_{1,2}) = n_0 - \delta\left(\frac{r_{1,2}}{a}\right)^{2m}$$

with m = 4. Again typical values for a Corning or ITT graded index fiber are used; i.e., $n_0 = 1.48$, $\delta = 0.02$, $a = 25\mu m$. Results have been obtained for

$$w = 2.5\mu m, 5\mu m$$

$$d = 8\mu m, 12\mu m, 16\mu m$$

where d is the separation distance and w is the beam waist radius. Specific results are given in Figures 13. Displayed in Figs. 14 is the % power in one fiber as a function of longitudinal distance for various separations.

Case 3 Coupling between two unequal fibers.

It is of interest to learn, when two unequal size fibers are placed side by side, whether transfer of power would occur for the multimode case. The following fibers were used:

$$n(r_{1,2}) = n_0 - \delta\left(\frac{r_{1,2}}{a_{1,2}}\right)^{2m}$$

$n_0 = 1.48$ $\quad m = 1, 4$

$\delta = 0.02$

$a_1 = 25\mu m$

$a_2 = 12.5\mu m$

Separation distance, $d = 8\mu m, 12\mu m$

Initial Beam Radius, $w = 5\mu m, 10\mu m$

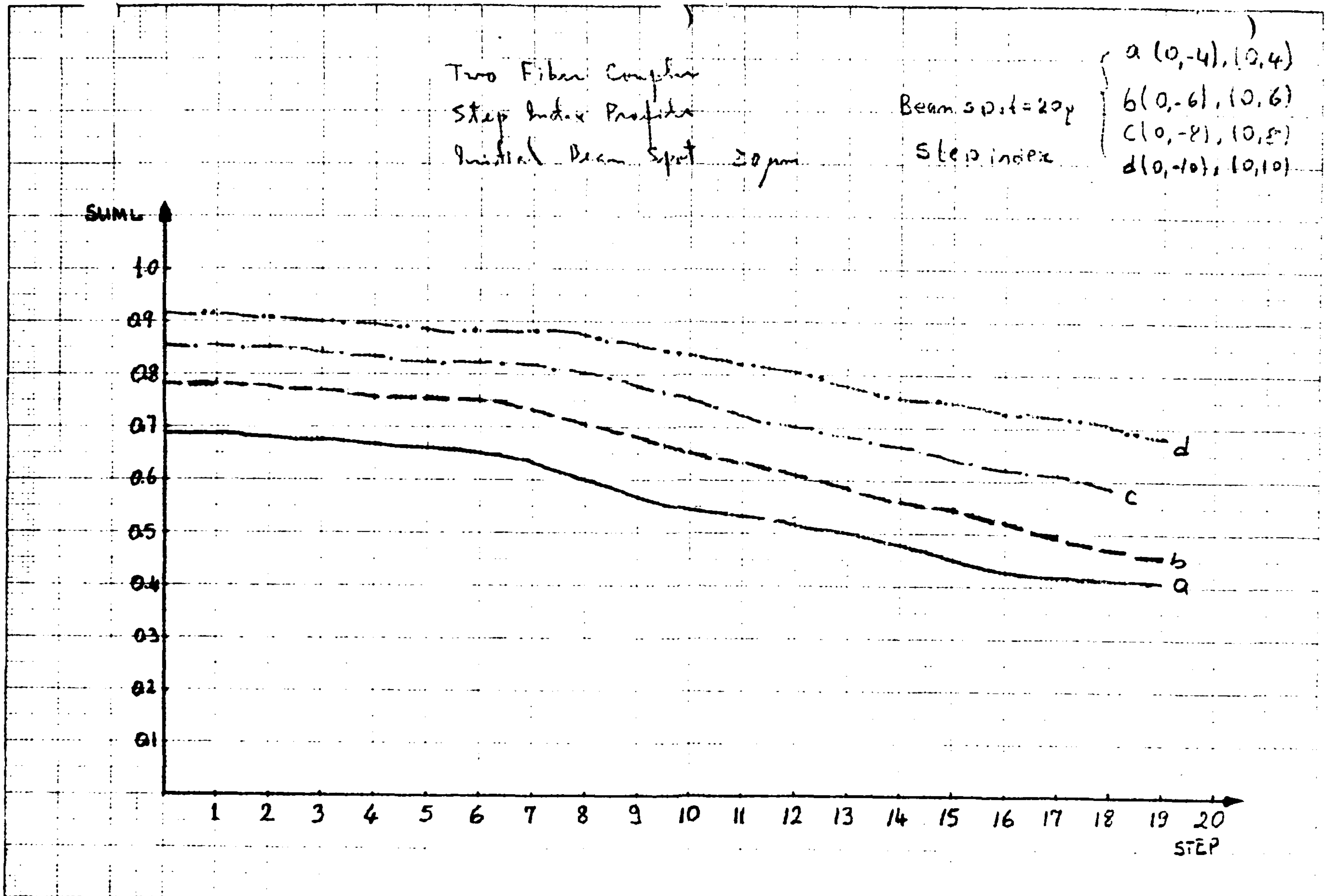

Two Fiber Coupler
Step Index Profile
Initial Beam Spot 20 μm
Beam spot = 20μ
Step index
a (0,-4), (0,4)
b (0,-6), (0,6)
c (0,-8), (0,8)
d (0,-10), (0,10)
SUML
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
STEP
a
b
c
d

FIG 14

For the above chosen parameters, one may observe from Figs. 15-16 that only nominal coupling occurs between two unequal size fibers. In other words these structures are not efficient couplers.

Case 4 Coupling between more than two fibers.

As illustrations, we have considered two types of structures: Three equal size fibers located equal-distance from each other and three unequal size fibers arranged in a triangle shape. One fiber is initially illuminated, we wish to learn the power exchange characteristics in these two couplers. The following parameters were used:

$$n(r_{1,2,3}) = n_0 - \delta\left(\frac{r_{1,2,3}}{a_{1,2,3}}\right)^2$$

$n_0 = 1.48$

$\delta = 0.02$

$a_1 = 25\mu m$

$a_2 = 25\mu m,\ 20\mu m$

$a_3 = 25\mu m,\ 15\mu m$

Separation distances, $d_1 = d_2 = d_3 = 12\mu m$

Initial beam radius, $w = 5\mu m$

It can be seen from Fig.17 that when one of the fiber of 3 identical fibers, separated an equal distance from each other, is illuminated with a gaussian beam, power exchange takes place between two unilluminated fibers with the one illuminated fiber in a synchronous manner. In other words, each of the originally unilluminated fibers is receiving identical amount of power transfer from the illuminated one, as expected. On the other hand, the power exchange phenomenon for 3 non-identical fibers coupler is much more complicated as seen from Fig.18

Larger power transfer tends to take place among fibers with similar ...

Fiber coupler is one of the crucial components in any fiber optics system. As such, one must understand the detailed wave interaction phenomenon in this type of coupler so that correct design can be made. We have demonstrated the capability of our technique in dealing with this type of fiber structures. Systematic studies of different variaties of fiber couplers may now be undertaken.

(d) Reflection Coefficient Calculations.

We have implemented the heuristic approach discussed earlier in the computer program to yield reflection coefficients for waves propagating in the various multimode fiber structures. Although it is difficult to justify the accuracy of the absolute values for the reflection coefficients obtained according to this algorithm, nevertheless, we feel that their relative values for different structures can be believed. This is because our heuristic approach took into consideration the fundamental characteristic of wave reflection: i.e., reflection occurs when discontinuity of the propagation medium or structure is experienced by the wave. The larger is the discontinuity, the larger will be the reflected energy.

Results for sample calculations for the reflection coefficients for various fiber structures are shown in Figs.19-20

IV. Conclusions and Recommendations

Support of this program has enabled the contractor to develop and perfect a computer program based on the scalar wave - FFT algorithm to study the propagation characteristics of guided waves in several important, practical fiber structures such as fibers with general index profiles (step index, parabolic index, ring index, etc), multi-channel fiber couplers, and fiber horns or tapers. These fiber structures may be made with commercially available fibers whose index variation may be as large as 1 - 2%.

We have implemented the adaptive coordinates and lossy outer mesh boundary schemes in our computer program. However, for most practical situations of interest in which the fiber core radius is about 25μm, the cladding index is about 1 - 2% less than the core index, the spot size of the beam is less than 20μm and the free-space wavelength of the beam is larger than 0.6μm, it is not necessary to implement the adaptive coordinates and lossy outer mesh boundary schemes. We also discovered that steep index gradient is not a hindrance for the program to produce accurate results as long as the scalar wave appraoch is still justifiable.

It is not unreasonable to ask the following question:

"Now that we have completed a beautiful program capable of producing propagation results for a variety of practical fiber structures, what can we do with it?"

The answer is "May be a lot!" Listed below are only a few of the problems that we can solve with this program:

(1) Any single-mode or multimode weakly guiding fiber with arbitrary refractive index profile.

Our program provides the means to obtain the propagation characteristics of guided waves supported by this structure. The core of the structure may be circular, elliptical, rectangular, triangular or dumb-bell

shape with general index profile.[8]

(2) Any fiber couplers composed of parallel strands of two or more of the above fibers. This is the only program which can provide the detailed coupling characteristics of this type of structure. Prior knowledge of coupling characteristics of a coupler is the key to successfully design and construct fiber couplers.

(3) Any transition elements derived from the above fibers. Transition elements such as tapers, horns, or mode converters or branches can all be analyzed by our program.

Recommended Future Research

In addition to the important practical problems mentioned above that can be solved by our approach, it is worthwhile to look into the future and seek out problems of potential importance and interest. For example:

(1) Nonlinear Fiber.
Very high intensity is achievable in fibers. One may wish to learn the propagation characteristics of waves in a fiber in which the induced nonlinearity of the medium plays a significant role. This problem may be solved by the scalar wave - FFT approach.

(2) Mode Conversion in a Fiber Due to its statistically Varying Medium.
This problem may also be approached from the scalar wave - FFT point of view. It is known that the presence of frozen-in statistically varying medium contributes to the mode conversion phenomenon in a fiber.[9] A systematic study of this problem will reveal the severity of this effect in changing the dispersion characteristics of beam in this fiber.

(3) Large-size Single-Mode Fiber
The advantages of having large-size single-mode fiber are well-known. Ring-index fiber as proposed by L Eyges of RADC appears

to be a promising one. Other type of fiber whose index variation may be radially unsymmetrical, such as, a layered fiber as shown in Fig. 21 may also be promising. Research should be encouraged on this type of fibers.

(4) Polarization Preserving Fibers

One of the main features of a weakly guiding fiber which can be analyzed by the scalar wave approach is that the guiding structure is polarization insensitive. However, for several important application areas, the polarization preserving characteristic of fiber is essential. Stress induced birefringent fiber or deformed core fiber may satisfy the needed requirement. However, to achieve the targeted isolation for the two orthogonal dominant modes, the required stress is excessively high for stress induced birefringent fiber and the loss is excessive for deformed-core fiber. We propose the use of layered dielectrics as shown in Fig. 21 to produce an equivalent birefringent effect to enable proper isolation for the two orthogonal dominant modes.[10] Initial indication is very promising. It would therefore be very worthwhile to pursue this research.

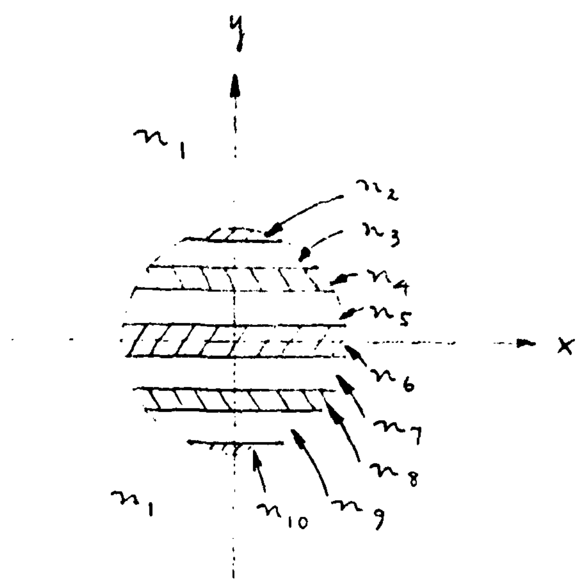


FIG. 21 Polarization Preserving Layered Fiber

Personnel:

The principal contributors of this contract have been:

C. Yeh	Senior Research Engineer
P. Barber	Research Engineer
F. Manshadi	Research Engineer

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10. Patent Pending.

SAMPLE PROGRAM LISTINGS FOR THE CASE OF BEAM PROPAGATION IN A STEP INDEX FIBER

CORE SIZE (DIAMETER) = 50μm
CORE INDEX = 1.48
CLADDING INDEX = 1.46
INITIAL GAUSSIAN BEAM SPOT SIZE (DIAMETER) = 40μm
WAVELENGTH = 0.8μm

(STEP INDEX CASE, m = 6)

```
LEVEL 2.3 . (JUNE 78)                    OS/360    FORTRAN H EXTENDED              DATE 80.19   1.57.04

REQUESTED OPTIONS:

OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(2) LINECOUNT(56) SIZE(MAX) AUTODBL(NONE)
                   SOURCE EBCDIC NOLIST NODECK OBJECT MAP NOFORMAT GOSTMT NOXREF ALC NOANSF NOTERM IBM FLA

                C
                C THIS PROGRAM CONTAINS:CORRECTED FIBRUN=N(OPTFIB,PRNTER,PEAK,SIZE,
                C HARM,GREYSC).
                C
                C      PROGRAM OPTFIB(INPUT,OUTPUT,FILED,TAPE5=INPUT,TAPE6=OUTPUT,        OPTFIB
                C     + TAPE7=FILED)                                                      OPTFIB
                C                                                                         OPTFIB
                C      INPUT PARAMETERS                                                   OPTFIB
                C CARD 1 (I5 FORMAT)                                                      OPTFIB
                C      NCASES   NUMBER OF CASES TO BE READ                                OPTFIB
                C CARD 2 (NAMELIST FORMAT-$DFAULT $                                       OPTFIB
                C      LAMBDA   WAVE LENGTH (MICRONS)                                     OPTFIB
                C      RO       1/E POINT IN IRRADIANCE (MICRONS)                         OPTFIB
                C      FR       FIBER RADIUS (MICRONS)                                    OPTFIB
                C      NO       REFRACTIVE INDEX                                          OPTFIB
                C      PCORP    PERCENT DROP AT R=FR OF N/NO                              OPTFIB
                C      OUTRAD   OUTER RADIUS (MICRONS)                                    OPTFIB
                C      DX       MESH SPACING (MICRONS)                                    OPTFIB
                C      NSTEPS   NUMBER OF Z-STEPS                                         OPTFIB
                C      NDZINC   LENGTH OF Z-STEP = ZMIN/NDZINC                            OPTFIB
                C      IOUT     DEVICE NUMBER FOR OUTPUT                                  OPTFIB
                C      IGREY    DEVICE NUMBER FOR GREYSC OUTPUT                           OPTFIB
                C      PGREY    IF TRUE PRINT IRRADIANCE PROFILE AT EACH STEP             OPTFIB
                C      PWAIST   IF TRUE WRITE 2ND MOMENTS AT EACH STEP                    OPTFIB
                C      PLTWST   IF TRUE PLOT 2ND MOMENTS VS DISTANCE                      OPTFIB
                C      PLTMAX   IF TRUE PLOT PEAK INTENSITY VS DISTANCE                   OPTFIB
                C      PLTFLD   IF TRUE PLOT FIELD IRRAD AT END OF PROPAGATION ALONG I    OPTFIB
                C      PLTFLE   IF TRUE DO ABOVE PLOT AT EVERY STEP                       OPTFIB
                C      MESH     GRID SIZE (32, 64, OR 128)                                OPTFIB
                C                                                                         OPTFIB
ISN 0002               COMMON /LCM2/REFNDX(16384),SN(128),CS(128),ZTSQ(128),PQSQ(128)     LCM2
                      + ,AMPARY(16384),RADARY(16384)                                      LCM2
                C      LEVEL 2,REFNDX,SN,CS,ZTSQ,PQSQ,AMPARY,RADARY                       LCM2
ISN 0003               DIMENSION WORK(256),MM(3),INV(32),S(32)                            OPTFIB
ISN 0004               DIMENSION XO(3),YO(3),PCDRPA(3),FRA(3),REFCFA(3)                   TEMP
ISN 0005               COMMON  /ARRAYS/V(32768)                                           ARRAYS
ISN 0006               COMMON /PARAM/DZINC,MESH,LAMBDA,RO,FR,NO,PCORP,OUTRAD,DX,NSTEPS,   PARAM
                      + NDZINC,MESHSQ,MSHSQ2,PI,WAVENO,DXSI,MS,NS,MF,NF,MSHPTS            PARAM
ISN 0007               COMMON /PRNTPL/PGREY,PWAIST,PLTWST,PLTMAX,LAST,IOUT,IGREY          PRNPLT
                      + ,PLTFLD,PLTFLE                                                    PRNTPLT
                C                                                                         OPTFIB
ISN 0008               REAL LAMBDA,NO,NOSQ,N2                                             OPTFIB
ISN 0009               LOGICAL PGREY,PWAIST,PLTWST,PLTMAX,PLTFLD,PLTFLE,LAST,CALLPR       OPTFIB
                C                                                                         OPTFIB
ISN 0010               DATA ICNTCS/1/,ICNT/0/                                             OPTFIB
                C                                                                         OPTFIB
ISN 0011               NAMELIST /DFAULT/LAMBDA,RO,NO,PCORP,OUTRAD,DX,NSTEPS,NDZINC,       OPTFIB
                      + IOUT,IGREY,PGREY,PWAIST,PLTWST,PLTMAX,PLTFLD,PLTFLE,MESH          OPTFIB
                C                                                                         OPTFIB
```

```
ISN 0012              READ(5,1000) NCASES                                                  OPTFIB
ISN 0013              WRITE(6,1000) NCASES
ISN 0014              READ(5,11)XB,YB                                                      TEMP
ISN 0015              WRITE(6,11)XB,YB
ISN 0016              READ(5,1000) NFIB                                                    TEMP
ISN 0017              WRITE(6,1000) NFIB
ISN 0018              READ(5,12)(XO(I),YO(I),I=1,NFIB)                                     TEMP
ISN 0019              WRITE(6,12)(XO(I),YO(I),I=1,NFIB)                                    TEMP
ISN 0020              READ(5,13)(PCORPA(K),K=1,NFIB)                                       TEMP
ISN 0021              READ(5,11)(FRA(K),K=1,NFIB)                                          TEMP
ISN 0022              WRITE(6,13)(PCORPA(K),K=1,NFIB)                                      TEMP
ISN 0023              WRITE(6,11)(FRA(K),K=1,NFIB)                                         TEMP
ISN 0024         1000 FORMAT(2X,I2)                                                        OPTFIB
ISN 0025           11 FORMAT(1X,F4.1,1X,F4.1)
ISN 0026           12 FORMAT(1X,F4.1,1X,F4.1,1X,F4.1,1X,F4.1)
ISN 0027           13 FORMAT(1X,F12.5,1X,F12.5)
               CI     READ(5,DFAULT)                                                       OPTFIB
               C                                                                           OPTFIB
ISN 0028              MN(1)= 7
ISN 0029              MN(2)= 7
ISN 0030              MN(3)= 0
ISN 0031              ICNT=0                                                               OPTFIB
ISN 0032              FLAG=NO/ABS(NO)                                                      OPTFIB
ISN 0033              NO=ABS(NO)                                                           OPTFIB
ISN 0034              IF(FLAG.LT.0.) WRITE(IOUT,2050)                                      OPTFIB
ISN 0036         2050 FORMAT(/,47H THE REFRACTIVE INDEX IS A CONSTANT EQUAL TO NO)         OPTFIB
ISN 0037              PCORP=PCORPA(1)                                                      TEMP
ISN 0038              FR=FRA(1)                                                            TEMP
ISN 0039              WRITE(IOUT,DFAULT)                                                   OPTFIB
               C                                                                           OPTFIB
               C      CALCULATE CONSTANTS                                                  OPTFIB
               C                                                                           OPTFIB
ISN 0040              MESH2=2*MESH                                                         OPTFIB
ISN 0041              MESHSQ=MESH**2                                                       OPTFIB
ISN 0042              MSHSQ2=2*MESHSQ                                                      OPTFIB
ISN 0043              RN2NO=.02*PCORP/FR**2                                                OPTFIB
ISN 0044              ZMIN=PI/(2.*SQRT(RN2NO))                                             OPTFIB
ISN 0045              DZINC=ZMIN/NDZINC                                                    OPTFIB
ISN 0046              DXSI=DZINC/ZMIN                                                      OPTFIB
ISN 0047              DXSIH=DXSI/2.                                                        OPTFIB
ISN 0048              DZET=DX/RO                                                           OPTFIB
ISN 0049              WAVENM=2.*PI/LAMBDA                                                  OPTFIB
ISN 0050              BETAHT=(2.*ZMIN*DXSI/(WAVENM*NO))*(PI/(MESH*DZET*RO))**2             OPTFIB
ISN 0051              FTCNST=(1.-1./MESH)*PI                                               OPTFIB
ISN 0052              XYO=MESH/2.                                                          OPTFIB
ISN 0053              RADNRM=(OUTRAD/RO)**2                                                OPTFIB
ISN 0054              RNORM=1./MESHSQ                                                      OPTFIB
ISN 0055              N2=NO*RN2NO                                                          OPTFIB
ISN 0056              REFCF=N2*RO**2/2.                                                    OPTFIB
ISN 0057              ALPHA=2.*ZMIN/(PI*WAVENM*NO*RO**2)                                   OPTFIB
ISN 0058              NOSQ=NO**2                                                           OPTFIB
ISN 0059              XSIMUL=DXSI                                                          OPTFIB
ISN 0060              LAST=.FALSE.                                                         OPTFIB
ISN 0061              IF(FLAG.LT.0.) REFCF=0.                                              OPTFIB
```

```
ISN 0063            CALLPR=PGREY.OR.PWAIST.OR.P_TWST.OR.P_TMAX.OR.PLTFLD.OR.PLTFLE      OPTFIB
               C                                                                          OPTFIB
               C    WRITE THE IMPORTANT CALCULATED PARAMETERS                             OPTFIB
               C                                                                          OPTFIB
ISN 0064            WRITE(IOUT,2000) ZMIN,DZINC,RN2ND,ALPHA                               OPTFIB
ISN 0065       2000 FORMAT(/,8H ZMIN = ,F10.4,1X,7HMICRONS,/,9H DZINC = ,F10.4,1X,        OPTFIB
                   + 7HMICRONS,/,9H RN2ND = ,E10.3,1X,13HMICRONS**(-2),/,                 OPTFIB
                   + 9H ALPHA = ,F10.5,/)                                                 OPTFIB
               C                                                                          OPTFIB
               C    CALCULATE NECESSARY ARRAYS                                            OPTFIB
               C                                                                          OPTFIB
ISN 0066            MP=6                                                                  TEMP
ISN 0067            DO 800 K=1,NFIB                                                       TEMP
ISN 0068            XO(K)=XO(K)+XYO                                                       TEMP
ISN 0069            YO(K)=YO(K)+XYO                                                       TEMP
ISN 0070            MX=2*MP
ISN 0071            REFCFA(K)=NO*.02*PCORPA(K)*(RO/RA(K))**MX/2.                          TEMP
ISN 0072        800 CONTINUE                                                              TEMP
ISN 0073            DO 100 K=1,MESH                                                       OPTFIB
ISN 0074            RK=K-1                                                                OPTFIB
ISN 0075            ARG=FTCNST*RK                                                         OPTFIB
ISN 0076            CS(K)=COS(ARG)                                                        OPTFIB
ISN 0077            SN(K)=SIN(ARG)                                                        OPTFIB
ISN 0078            ZTSQ(K)=((RK-XYO)*DZET)**2                                            OPTFIB
ISN 0079            PQSQ(K)=(RK-XYO+.5)**2                                                OPTFIB
ISN 0080        100 CONTINUE                                                              OPTFIB
               C                                                                          OPTFIB
               C    SET UP REFRACTIVE INDEX ARRAY                                         OPTFIB
               C                                                                          OPTFIB
ISN 0081            M=0                                                                   OPTFIB
ISN 0082            DO 120 J=1,MESH                                                       OPTFIB
ISN 0083            DO 120 I=1,MESH                                                       TEMP
ISN 0084            M=M+1                                                                 TEMP
ISN 0085            TMPNDX=0.                                                             TEMP
ISN 0086            DO 110 K=1,NFIB                                                       TEMP
ISN 0087            Z1=((J-1.-YO(K))*DZET)**2                                             TEMP
ISN 0088            Z2=((I-1.-XO(K))*DZET)**2                                             TEMP
ISN 0089            RAD=Z1+Z2                                                             TEMP
ISN 0090            TMPNDX=AMAX1(TMPNDX,(NO-REFCFA(K)*(RAD**MP)))                           T
ISN 0091            CREF=NO*(1.-0.01*PCORPA(K))
ISN 0092            REFNDX(M)=AMAX1(TMPNDX,CREF)
ISN 0093        110 CONTINUE                                                              TEMP
               C     IF(I.EQ.52.OR.I.EQ.58) WRITE(IOUT,*) REFNDX(M)                       TEMP
ISN 0094        120 CONTINUE                                                              OPTFIB
ISN 0095            IF(MESH.NE.128) GO TO 10                                              OPTFIB
ISN 0097            MS=MESH/4+1                                                           OPTFIB
ISN 0098            MF=MS+MESH/2-1                                                        OPTFIB
ISN 0099            NS=MS                                                                 OPTFIB
ISN 0100            NF=MF                                                                 OPTFIB
ISN 0101            GO TO 40                                                              OPTFIB
ISN 0102         10 CONTINUE                                                              OPTFIB
ISN 0103            MS=1                                                                  OPTFIB
ISN 0104            NS=1                                                                  OPTFIB
ISN 0105            MF=MESH                                                               OPTFIB
```

```
ISN 0106              NF=MESH                                                            OPTFIB
ISN 0107        40    CONTINUE                                                           OPTFIB
ISN 0108              CALL GREYSC(IGREY,10,REFNDX,MESH,MESH,MS,MF,1,NS,NF,1,0.,0.,
                     *6HREFNDX,6)
ISN 0109              DO 130 K=1,MESHSQ                                                  OPTFIB
ISN 0110              REFNDX(K)=REFNDX(K)**2-NOSQ                                        OPTFIB
ISN 0111       130    CONTINUE                                                           OPTFIB
             C        CALL GREYSC(IGREY,10,REFNDX,MESH,MESH,MS,MF,1,NS,NF,1,0.,0.,       TEMP
             C       * 6HREFNDX,6)                                                       TEMP
             C                                                                           OPTFIB
             C        SET UP INITIAL FIELD                                               OPTFIB
             C                                                                           OPTFIB
ISN 0112              CLOSS=0.
ISN 0113              M=-1                                                               OPTFIB
ISN 0114              K=0                                                                OPTFIB
ISN 0115              CH=WAVENM*ZMIN*DXSIH/(2.*NU)                                       OPTFIB
ISN 0116              DO 140 J=1,MESH                                                    OPTFIB
ISN 0117              Z1=((J-XYO-YB-1)*DZET)**2                                          TEMP
ISN 0118              BZ1=((J-XYO-1)*DZET)**2
ISN 0119              DO 140 I=1,MESH                                                    OPTFIB
ISN 0120              K=K+1                                                              OPTFIB
ISN 0121              M=M+2                                                              OPTFIB
ISN 0122              MP1=M+1                                                            OPTFIB
ISN 0123              Z2=((I-XYO-XB-1)*DZET)**2                                          TEMP
ISN 0124              BZ2=((I-XYO-1)*DZET)**2
ISN 0125              BRAD=BZ1+BZ2
ISN 0126              RAD=Z1+Z2                                                          OPTFIB
ISN 0127              AMP=EXP(-RAD/2.)                                                   OPTFIB
ISN 0128              IF(BRAD.GT.RADNRM) AMP=EXP(-RAD/2.-CLOSS)
ISN 0130              ARG=CH*REFNDX(K)                                                   OPTFIB
ISN 0131              V(M)=AMP*COS(ARG)                                                  OPTFIB
ISN 0132              V(MP1)=AMP*SIN(ARG)                                                OPTFIB
ISN 0133       140    CONTINUE                                                           OPTFIB
ISN 0134              IF(CALLPR) CALL PRNTER(ICNT)                                       OPTFIB
             C                                                                           OPTFIB
             C        DO PROPAGATION                                                     OPTFIB
             C                                                                           OPTFIB
ISN 0136              DO 500 ICNT=1,NSTEPS                                               OPTFIB
             C                                                                           OPTFIB
             C        CONDITION V FOR TRANSFORM                                          OPTFIB
             C                                                                           OPTFIB
ISN 0137              K=-1                                                               OPTFIB
ISN 0138              DO 160 J=1,MESH                                                    OPTFIB
ISN 0139              SNJ=SN(J)                                                          OPTFIB
ISN 0140              CSJ=CS(J)                                                          OPTFIB
ISN 0141              DO 160 I=1,MESH                                                    OPTFIB
ISN 0142              K=K+2                                                              OPTFIB
ISN 0143              KP1=K+1                                                            OPTFIB
ISN 0144              SNI=SN(I)                                                          OPTFIB
ISN 0145              CSI=CS(I)                                                          OPTFIB
ISN 0146              AR=CSJ*CSI-SNJ*SNI                                                 OPTFIB
ISN 0147              AI=-(CSJ*SNI+CSI*SNJ)                                              OPTFIB
ISN 0148              VR=V(K)                                                            OPTFIB
ISN 0149              VI=V(KP1)                                                          OPTFIB
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LEVEL 2.3.  ( JUNE 78)          MAIN          OS/360   FORTRAN H EXTENDED          DATE 80.199   1.57.04

ISN 0150                V(K)=VR*AR-VI*AI                                         OPTFIB
ISN 0151                V(KP1)=VI*AR+VR*AI                                       OPTFIB
ISN 0152         160    CONTINUE                                                 OPTFIB
                  C                                                              OPTFIB
                  C     DO TRANSFORM                                             OPTFIB
                  C                                                              OPTFIB
ISN 0153                CALL HARM(V,MM,INV,S,1,IFERR)                            OPTFIB
                  C                                                              OPTFIB
                  C     SOLVE FIRST ORDER ODE                                    OPTFIB
                  C                                                              OPTFIB
ISN 0154                K=-1                                                     OPTFIB
ISN 0155                DO 180 J=1,MESH                                          OPTFIB
ISN 0156                PHI1=BETAHT*POSQ(J)                                      OPTFIB
ISN 0157                DO 180 I=1,MESH                                          OPTFIB
ISN 0158                K=K+2                                                    OPTFIB
ISN 0159                KP1=K+1                                                  OPTFIB
ISN 0160                PHI2=BETAHT*POSQ(I)                                      OPTFIB
ISN 0161                VR=V(K)                                                  OPTFIB
ISN 0162                VI=V(KP1)                                                OPTFIB
ISN 0163                ANG=-(PHI1+PHI2)                                         OPTFIB
ISN 0164                CANG=COS(ANG)                                            OPTFIB
ISN 0165                SANG=SIN(ANG)                                            OPTFIB
ISN 0166                V(K)=(VR*CANG-VI*SANG)                                   OPTFIB
ISN 0167                V(KP1)=(VR*SANG+VI*CANG)                                 OPTFIB
ISN 0168         180    CONTINUE                                                 OPTFIB
                  C                                                              OPTFIB
                  C     DO INVERSE TRANSFORM                                     OPTFIB
                  C                                                              OPTFIB
ISN 0169                CALL HARM(V,MM,INV,S,-1,IFERR)                           OPTFIB
                  C                                                              OPTFIB
                  C     RECONDITION V BECAUSE OF TRANSFORM                       OPTFIB
                  C                                                              OPTFIB
ISN 0170                K=-1                                                     OPTFIB
ISN 0171                DO 200 J=1,MESH                                          OPTFIB
ISN 0172                SNJ=SN(J)                                                OPTFIB
ISN 0173                CSJ=CS(J)                                                OPTFIB
ISN 0174                BZ1=((J-XYO-1)*DZET)**2
ISN 0175                CLOSS=2.
ISN 0176                DO 200 I=1,MESH                                          OPTFIB
ISN 0177                BZ2=((I-XYO-1)*DZET)**2
ISN 0178                BRAD=BZ1+BZ2
ISN 0179                CM=1.
ISN 0180                IF(BRAD.GT.RADNRM) CM=EXP(-CLOSS*(BRAD-RADNRM))
ISN 0182                K=K+2                                                    OPTFIB
ISN 0183                KP1=K+1                                                  OPTFIB
ISN 0184                SNI=SN(I)                                                OPTFIB
ISN 0185                CSI=CS(I)                                                OPTFIB
ISN 0186                AR=CSJ*CSI-SNJ*SNI                                       OPTFIB
ISN 0187                AI=CSJ*SNI+SNJ*CSI                                       OPTFIB
ISN 0188                VR=V(K)*CM
ISN 0189                VI=V(KP1)*CM
ISN 0190                V(K)=VR*AR-VI*AI                                         OPTFIB
ISN 0191                V(KP1)=VR*AI+VI*AR                                       OPTFIB
ISN 0192         200    CONTINUE                                                 OPTFIB
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LEVEL 2.3.0 (JUNE 78)            MAIN           OS/360   FORTRAN H EXTENDED             DATE 80.199/21.57.04
                C                                                                              OPTFIB
                C      NOW INCLUDE EITHER FULL STEP OR HALF STEP REFRACTIVE                    OPTFIB
                C      INDEX EFFECTS DEPENDING ON WHERE IN THE PATH YOU ARE                    OPTFIB
                C                                                                              OPTFIB
  ISN 0193             IF(ICNT.EQ.NSTEPS) XSIMUL=DXSIM                                         OPTFIB
  ISN 0195             K=-1                                                                    OPTFIB
  ISN 0196             CH=WAVENN*ZMIN*XSIMUL/(2.*NJ)                                           OPTFIB
  ISN 0197             DO 220 M=1,MESHSQ                                                       OPTFIB
  ISN 0198             ARG=REFNDX(M)*CH                                                        OPTFIB
  ISN 0199             AR=COS(ARG)                                                             OPTFIB
  ISN 0200             AI=SIN(ARG)                                                             OPTFIB
  ISN 0201             K=K+2                                                                   OPTFIB
  ISN 0202             KP1=K+1                                                                 OPTFIB
  ISN 0203             VR=V(K)                                                                 OPTFIB
  ISN 0204             VI=V(KP1)                                                               OPTFIB
  ISN 0205             V(K)=VR*AR-VI*AI                                                        OPTFIB
  ISN 0206             V(KP1)=VR*AI+VI*AR                                                      OPTFIB
  ISN 0207        220  CONTINUE                                                                OPTFIB
  ISN 0208             IF(ICNT.EQ.NSTEPS) LAST=.TRUE.                                          OPTFIB
  ISN 0210             IF(CALLPR) CALL PRNTER(ICNT)                                            OPTFIB
  ISN 0212        500  CONTINUE                                                                OPTFIB
                C                                                                              OPTFIB
                C      CALCULATE IRRADIANCE PATTERN AND PRINT                                  OPTFIB
                C                                                                              OPTFIB
  ISN 0213             IF(PGREY) GO TO 30                                                      OPTFIB
  ISN 0215             M=0                                                                     OPTFIB
  ISN 0216             DO 240 K=1,MSHSQ2,2                                                     OPTFIB
  ISN 0217             KP1=K+1                                                                 OPTFIB
  ISN 0218             VR=V(K)                                                                 OPTFIB
  ISN 0219             VI=V(KP1)                                                               OPTFIB
  ISN 0220             M=M+1                                                                   OPTFIB
  ISN 0221             RADARY(M)=VR**2+VI**2                                                   OPTFIB
  ISN 0222        240  CONTINUE                                                                OPTFIB
  ISN 0223             CALL GREYSC(IGREY,10,RADARY,MESH,MESH,MS,MF,1,NS,NF,1.0,.0.,            OPTFIB
                     * 10HIRRADIANCE,10)                                                       OPTFIB
  ISN 0224         30  CONTINUE                                                                OPTFIB
  ISN 0225             ICNTCS=ICNTCS+1                                                         OPTFIB
                C      IF(ICNTCS.LE.NCASES) GO TO 1                                            OPTFIB
  ISN 0226             STOP
  ISN 0227             END                                                                     OPTFIB
*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(2) LINECOUNT(55) SIZE(MAX) AUTODBL(NONE)
*OPTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF ALC NOANSF NOTERM IBM FLA
*STATISTICS*     SOURCE STATEMENTS =      226, PROGRAM SIZE =      5316, SUBPROGRAM NAME =  MAIN
*STATISTICS*  NO  DIAGNOSTICS GENERATED
****** END OF COMPILATION ******                                          68K BYTES OF CORE NOT USED
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LEVEL 2.3.0 (JUNE 79)                    OS/360    FORTRAN H EXTENDED            DATE 80.195   1.57.07

REQUESTED OPTIONS:

OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(2) LINECOUNT(56) SIZE(MAX) AUTODBL(NONE)
                   SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF ALC NOANSF NOTERM IBM FLA

  ISN 0002            SUBROUTINE PEAK(VMAX)                                               PEAK
  ISN 0003            COMMON /LCM2/REFNDX(16384),SN(128),CS(129),ZTSQ(128),PQSQ(128)      LCM2
                     * ,AMPARY(16384),RADARY(16384)                                       LCM2
                C     LEVEL 2,REFNDX,SN,CS,ZTSQ,PQSQ,AMPARY,RADARY                        LCM2
  ISN 0004            COMMON  /ARRAYS/V(32768)                                            ARRAYS
  ISN 0005            COMMON /PARAM/DZINC,MESH,LAMBDA,RO,FR,N),PCONP,OUTRAD,DX,NSTEPS,    PARAM
                     * NOZINC,MESHSQ,MSHSQ2,PI,WAVENM,DXSQ,MS,NS,MF,NF,MSHPTS             PARAM
  ISN 0006            L=0                                                                 PEAK
  ISN 0007            SUML=0.                                                             TEMP
  ISN 0008            SUMR=0.                                                             TEMP
  ISN 0009            VMAX=0.                                                             PEAK
  ISN 0010            DO 10 K=1,MSHSQ2,2                                                  PEAK
  ISN 0011            VR=V(K)                                                             PEAK
  ISN 0012            L=L+1                                                               PEAK
  ISN 0013            KP1=K+1                                                             PEAK
  ISN 0014            VI=V(KP1)                                                           PEAK
  ISN 0015            VRAD=VI**2+VR**2                                                    PEAK
  ISN 0016            IF(K.LE.MESHSQ) SUML=SUML+VRAD                                      TEMP
  ISN 0018            IF(K.GE.MESHSQ) SUMR=SUMR+VRAD                                      TEMP
  ISN 0020            VMAX=AMAX1(VMAX,VRAD)                                               PEAK
  ISN 0021            RADARY(L)=VRAD                                                      PEAK
  ISN 0022        10  CONTINUE                                                            PEAK
  ISN 0023            TOT=SUML+SUMR                                                       TEMP
  ISN 0024            SUML=SUML/TOT                                                       TEMP
  ISN 0025            SUMR=SUMR/TOT                                                       TEMP
  ISN 0026            WRITE(6,2000) SUML,SUMR                                             TEMP
  ISN 0027      2000  FORMAT(/,1X,7HSUML = ,E14.7,3X,7HSUMR = ,E14.7,/)                   TEMP
  ISN 0028            RETURN                                                              PEAK
  ISN 0029            END                                                                 PEAK

*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(2) LINECOUNT(56) SIZE(MAX) AUTODBL(NONE)

*OPTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF ALC NOANSF NOTERM IBM FL

*STATISTICS*     SOURCE STATEMENTS =      28, PROGRAM SIZE =      540, SUBPROGRAM NAME =  PEAK

*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                                      112K BYTES OF CORE NOT USED
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LEVEL 2.3.  (JUNE 78)                    OS/360    FORTRAN H EXTENDED              DATE 80.199   .57.08

REQUESTED OPTIONS:

OPTIONS IN EFFECT:  NAME(MAIN) OPTIMIZE(2) LINECOUNT(56) SIZE(MAX) AUTODBL(NONE)
                    SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF ALC NOANSF NOTERM IBM FL/

     ISN 0002            SUBROUTINE SIZE(ARRAY,MESH,MESH,XO,YO,X2,Y2)                    SIZE
     ISN 0003            DIMENSION ARRAY(MESH,MESH)                                      SIZE
     ISN 0004            MID=MESH/2+1                                                    SIZE
     ISN 0005            SUM1=0.                                                         SIZE
     ISN 0006            SUM2=0.                                                         SIZE
     ISN 0007            SUM3=0.                                                         SIZE
     ISN 0008            SUM4=0.                                                         SIZE
     ISN 0009            SUM5=0.                                                         SIZE
     ISN 0010            DO 10 N=1,MESH                                                  SIZE
     ISN 0011            RN=N-MID                                                        SIZE
     ISN 0012            RNSQ=RN**2                                                      SIZE
     ISN 0013            DO 10 M=1,MESH                                                  SIZE
     ISN 0014            RM=M-MID                                                        SIZE
     ISN 0015            RMSQ=RM**2                                                      SIZE
     ISN 0016            ARMN = ARRAY(M,N)
     ISN 0017            SUM1=SUM1+RM*ARMN                                               SIZE
     ISN 0018            SUM2=SUM2+RN*ARMN                                               SIZE
     ISN 0019            SUM3=SUM3+RMSQ*ARMN                                             SIZE
     ISN 0020            SUM4=SUM4+RNSQ*ARMN                                             SIZE
     ISN 0021            SUM5=SUM5+ARMN                                                  SIZE
     ISN 0022      10    CONTINUE                                                        SIZE
     ISN 0023            SNORM=1./SUM5                                                   SIZE
     ISN 0024            XO=SNORM*SUM2                                                   SIZE
     ISN 0025            YO=SNORM*SUM1                                                   SIZE
     ISN 0026            X2=SNORM*SUM4-XO**2                                             SIZE
     ISN 0027            Y2=SNORM*SUM3-YO**2                                             SIZE
     ISN 0028            X2=SQRT(X2)                                                     SIZE
     ISN 0029            Y2=SQRT(Y2)                                                     SIZE
     ISN 0030            RETURN                                                          SIZE
     ISN 0031            END                                                             SIZE

*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(2) LINECOUNT(55) SIZE(MAX) AUTODBL(NONE)

*OPTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF ALC NOANSF NOTERM IBM FLA

*STATISTICS*     SOURCE STATEMENTS =       30, PROGRAM SIZE =       786, SUBPROGRAM NAME =  SIZE

*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                                  112K BYTES OF CORE NOT USED
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LEVEL 2.3.0 (JUNE 78)                    OS/360    FORTRAN H EXTENDED              DATE 80.19    1.57.09

REQUESTED OPTIONS:

OPTIONS IN EFFECT:  NAME(MAIN) OPTIMIZE(2) LINECOUNT(55) SIZE(MAX) AUTODBL(NONE)
                    SOURCE EBCDIC NOLIST NODECK OBJECT MAP NOFORMAT GOSTMT NOXREF ALC NOANSF NOTERM IBM FL/

                                                                                              INITIAL
   ISN 0002          BLOCK DATA                                                               ARRAYS
   ISN 0003          COMMON  /ARRAYS/V(32768)                                                 PARAM
   ISN 0004          COMMON /PARAM/DZINC,MESH,LAMBDA,RO,FR,NO,PCDRP,OUTRAD,DX,NSTEPS,         PARAM
                    + NDZINC,MESHSQ,MSHSQ2,PI,WAVENN,DXSI,MS,NS,MF,NF,MSHPTS                  PRNTPLT
   ISN 0005          COMMON /PRNTPL/PGREY,PWAIST,PLTWST,PLTMAX,LAST,IOUT,IGREY                 PRNTPLT
                    + ,PLTFLD,PLTFLE                                                          INITIAL
   ISN 0006          LOGICAL PGREY,PWAIST,PLTWST,PLTMAX,LAST                                  INITIAL
   ISN 0007          LOGICAL PLTFLD,PLTFLE                                                    INITIAL
   ISN 0008          REAL LAMBDA,NO                                                           INITIAL
   ISN 0009          DATA PGREY,PWAIST,PLTWST,PLTMAX,LAST,IOUT,IGREY/2*.TRUE.,2*.FALSE.       INITIAL
                    +,.FALSE.,2*6/                                                            INITIAL
   ISN 0010          DATA LAMBDA,RO,NO,PCDRP,OUTRAD,DX,NSTEPS,NDZINC
                    +    /0.80,20.0,1.48,.14E+1,62.0,.1E+01,40,5/                              INITIAL
   ISN 0011          DATA PLTFLD,PLTFLE/.FALSE.,.FALSE./                                      IN
   ISN 0012          DATA MESH/128/,PI/3.14159265/                                            INITIAL
   ISN 0013          END

*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(2) LINECOUNT(55) SIZE(MAX) AUTODBL(NONE)

*OPTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT MAP NOFORMAT GOSTMT NOXREF ALC NOANSF NOTERM IBM FL

*STATISTICS*     SOURCE STATEMENTS =      12, PROGRAM SIZE =        0, SUBPROGRAM NAME =ARRAYS

*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                                 112K BYTES OF CORE NOT USED
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```
REQUESTED OPTIONS:

OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(2) LINECOUNT(56) SIZE(MAX) AUTODBL(NONE)
                   SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF ALC NOANSF NOTERM IBM FL/

C        SUBROUTINE HARM
C
C        PURPOSE
C           PERFORMS DISCRETE COMPLEX FOURIER TRANSFORMS ON A COMPLEX
C           THREE DIMENSIONAL ARRAY
C
C        USAGE
C           CALL HARM (A,M,INV,S,IFSET,IFERR)
C
C        DESCRIPTION OF PARAMETERS
C           A      - AS INPUT, A CONTAINS THE COMPLEX, 3-DIMENSIONAL
C                    ARRAY TO BE TRANSFORMED.  THE REAL PART OF
C                    A(I1,I2,I3) IS STORED IN VECTOR FASHION IN A CELL
C                    WITH INDEX 2*(I3*N1*N2 + I2*N1 + I1) + 1 WHERE
C                    NI = 2**M(I), I=1,2,3 AND I1 = 0,1,...,N1-1 ETC.
C                    THE IMAGINARY PART IS IN THE CELL IMMEDIATELY
C                    FOLLOWING.  NOTE THAT THE SUBSCRIPT I1 INCREASES
C                    MOST RAPIDLY AND I3 INCREASES LEAST RAPIDLY.
C                    AS OUTPUT, A CONTAINS THE COMPLEX FOURIER
C                    TRANSFORM.  THE NUMBER OF CORE LOCATIONS OF
C                    ARRAY A IS 2*(N1*N2*N3)
C           M      - A THREE CELL VECTOR WHICH DETERMINES THE SIZES
C                    OF THE 3 DIMENSIONS OF THE ARRAY A.   THE SIZE,
C                    NI, OF THE I DIMENSION OF A IS 2**M(I), I = 1,2,3
C           INV    - A VECTOR WORK AREA FOR BIT AND INDEX MANIPULATION
C                    OF DIMENSION ONE FOURTH OF THE QUANTITY
C                    MAX(N1,N2,N3)
C           S      - A VECTOR WORK AREA FOR SINE TABLES WITH DIMENSION
C                    THE SAME AS INV
C           IFSET  - AN OPTION PARAMETER WITH THE FOLLOWING SETTINGS
C                       0    SET UP SINE AND INV TABLES ONLY
C                       1    SET UP SINE AND INV TABLES ONLY AND
C                            CALCULATE FOURIER TRANSFORM
C                      -1    SET UP SINE AND INV TABLES ONLY AND
C                            CALCULATE INVERSE FOURIER TRANSFORM (FOR
C                            THE MEANING OF INVERSE SEE THE EQUATIONS
C                            UNDER METHOD BELOW)
C                       2    CALCULATE FOURIER TRANSFORM ONLY (ASSUME
C                            SINE AND INV TABLES EXIST)
C                      -2    CALCULATE INVERSE FOURIER TRANSFORM ONLY
C                            (ASSUME SINE AND INV TABLES EXIST)
C           IFERR  - ERROR INDICATOR.   WHEN IFSET IS 0,+1,-1,
C                    IFERR = 1 MEANS THE MAXIMUM M(I) IS GREATER THAN
C                  20 , I=1,2,3   WHEN IFSET IS 2,-2 , IFERR = 1
C                    MEANS THAT THE SINE AND INV TABLES ARE NOT LARGE
C                    ENOUGH OR HAVE NOT BEEN COMPUTED .
C                    IF ON RETURN IFERR = 0 THEN NONE OF THE ABOVE
C                    CONDITIONS ARE PRESENT
C
```

```
                C       REMARKS
                C          THIS SUBROUTINE IS TO BE USED FOR COMPLEX, 3-DIMENSIONAL
                C          ARRAYS IN WHICH EACH DIMENSION IS A POWER OF 2.  THE
                C          MAXIMUM M(I) MUST NOT BE LESS THAN 3 OR GREATER THAN 20.
                C          I = 1,2,3
                C
                C       SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
                C          NONE
                C
                C       METHOD
                C          FOR IFSET = +1, OR +2, THE FOURIER TRANSFORM OF COMPLEX
                C          ARRAY A IS OBTAINED.
                C
                C                 N1-1   N2-1   N3-1                     L1    L2    L3
                C     X(J1,J2,J3)=SUM    SUM    SUM    A(K1,K2,K3)*W1   *W2   *W3
                C                 K1=0   K2=0   K3=0
                C
                C                 WHERE WI IS THE N(I) ROOT OF UNITY AND L1=K1*J1,
                C                       L2=K2*J2, L3=K3*J3
                C
                C
                C          FOR IFSET = -1, OR -2, THE INVERSE FOURIER TRANSFORM A OF
                C          COMPLEX ARRAY X IS OBTAINED.
                C
                C     A(K1,K2,K3)=
                C              1          N1-1   N2-1   N3-1                   -L1   -L2   -L3
                C          --------- *SUM    SUM    SUM    X(J1,J2,J3)*W1   *W2   *W3
                C          N1*N2*N3    J1=0   J2=0   J3=0
                C
                C
                C          SEE J.W. COOLEY AND J.W. TUKEY, 'AN ALGORITHM FOR THE
                C          MACHINE CALCULATION OF COMPLEX FOURIER SERIES',
                C          MATHEMATICS OF COMPUTATIONS, VOL. 19 (APR. 1965), P. 297.
                C
                C     ..................................................................
                C
ISN 0002              SUBROUTINE HARM(A,M,INV,S,IFSET, IFERR)
ISN 0003              DIMENSION A(1),INV(1),S(1),N(3),M(3),NP(3),W(2),W2(2),W3(2)
ISN 0004              EQUIVALENCE (N1,N(1)),(N2,N(2)),(N3,N(3))
ISN 0005           10 IF( IABS(IFSET) - 1) 900,900,12
ISN 0006           12 MTT=MAX0(M(1),M(2),M(3)) -2
ISN 0007              ROOT2 = SQRT(2.)
ISN 0008              IF (MTT-MT ) 14,14,13
ISN 0009           13 IFERR=1
ISN 0010              RETURN
ISN 0011           14 IFERR=0
ISN 0012              M1=M(1)
ISN 0013              M2=M(2)
ISN 0014              M3=M(3)
ISN 0015              N1=2**M1
ISN 0016              N2=2**M2
ISN 0017              N3=2**M3
ISN 0018           16 IF(IFSET) 18,18,20
ISN 0019           18 NX= N1*N2*N3
```

```
ISN 0020          FN = NX                                        HARM1070
ISN 0021          DO 19 I = 1,NX                                 HARM1080
ISN 0022          A(2*I-1) = A(2*I-1)/FN                         HARM1090
ISN 0023       19 A(2*I) = -A(2*I)/FN                            HARM1100
ISN 0024       20 NP(1)=N1*2                                     HARM1110
ISN 0025          NP(2)= NP(1)*N2                                HARM1120
ISN 0026          NP(3)=NP(2)*N3                                 HARM1130
ISN 0027          DO 250 ID=1,3                                  HARM1140
ISN 0028          IL = NP(3)-NP(ID)                              HARM1150
ISN 0029          IL1 = IL+1                                     HARM1160
ISN 0030          MI = M(ID)                                     HARM1170
ISN 0031          IF (MI)250,250,30                              HARM1180
ISN 0032       30 IDIF=NP(ID)                                    HARM1190
ISN 0033          KBIT=NP(ID)                                    HARM1200
ISN 0034          MEV = 2*(MI/2)                                 HARM1210
ISN 0035          IF (MI - MEV )60,60,40                         HARM1220
            C                                                    HARM1230
            C     M IS ODD. DO L=1 CASE                          HARM1240
ISN 0036       40 KBIT=KBIT/2                                    HARM1250
ISN 0037          KL=KBIT-2                                      HARM1260
ISN 0038          DO 50 I=1,IL1,IDIF                             HARM1270
ISN 0039          KLAST=KL+I                                     HARM1280
ISN 0040          DO 50 K=I,KLAST,2                              HARM1290
ISN 0041          KD=K+KBIT                                      HARM1300
            C                                                    HARM1310
            C     DO ONE STEP WITH L=1,J=0                       HARM1320
            C     A(K)=A(K)+A(KD)                                HARM1330
            C     A(KD)=A(K)-A(KD)                               HARM1340
            C                                                    HARM1350
ISN 0042          T=A(KD)                                        HARM1360
ISN 0043          A(KD)=A(K)-T                                   HARM1370
ISN 0044          A(K)=A(K)+T                                    HARM1380
ISN 0045          T=A(KD+1)                                      HARM1390
ISN 0046          A(KD+1)=A(K+1)-T                               HARM1400
ISN 0047       50 A(K+1)=A(K+1)+T                                HARM1410
ISN 0048          IF (MI - 1)250,250,52                          HARM1420
ISN 0049       52 LFIRST =3                                      HARM1430
            C                                                    HARM1440
            C     DEF - JLAST = 2**(L-2) -1                      HARM1450
ISN 0050          JLAST=1                                        HARM1460
ISN 0051          GO TO 70                                       HARM1470
            C                                                    HARM1480
            C     M IS EVEN                                      HARM1490
ISN 0052       60 LFIRST = 2                                     HARM1500
ISN 0053          JLAST=0                                        HARM1510
ISN 0054       70 DO 240 L=LFIRST,MI,2                           HARM1520
ISN 0055          JJDIF=KBIT                                     HARM1530
ISN 0056          KBIT=KBIT/4                                    HARM1540
ISN 0057          KL=KBIT-2                                      HARM1550
            C                                                    HARM1560
            C     DO FOR J=0                                     HARM1570
ISN 0058          DO 80 I=1,IL1,IDIF                             HARM1580
ISN 0059          KLAST=I+KL                                     HARM1590
ISN 0060          DO 80 K=I,KLAST,2                              HARM1600
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LEVEL 2.  ) (JUNE 78)          HARM          OS/360  FORTRAN H EXTENDED          DATE 80.15  21.57.09

ISN 0061          K1=K+KBIT                                                  HARM1610
ISN 0062          K2=K1+KBIT                                                 HARM1620
ISN 0063          K3=K2+KBIT                                                 HARM1630
            C                                                                HARM1640
            C     DO TWO STEPS WITH J=0                                      HARM1650
            C     A(K)=A(K)+A(K2)                                            HARM1660
            C     A(K2)=A(K)-A(K2)                                           HARM1670
            C     A(K1)=A(K1)+A(K3)                                          HARM1680
            C     A(K3)=A(K1)-A(K3)                                          HARM1690
            C                                                                HARM1700
            C     A(K)=A(K)+A(K1)                                            HARM1710
            C     A(K1)=A(K)-A(K1)                                           HARM1720
            C     A(K2)=A(K2)+A(K3)*I                                        HARM1730
            C     A(K3)=A(K2)-A(K3)*I                                        HARM1740
            C                                                                HARM1750
ISN 0064          T=A(K2)                                                    HARM1760
ISN 0065          A(K2)=A(K)-T                                               HARM1770
ISN 0066          A(K)=A(K)+T                                                HARM1780
ISN 0067          T=A(K2+1)                                                  HARM1790
ISN 0068          A(K2+1)=A(K+1)-T                                           HARM1800
ISN 0069          A(K+1)=A(K+1)+T                                            HARM1810
            C                                                                HARM1820
ISN 0070          T=A(K3)                                                    HARM1830
ISN 0071          A(K3)=A(K1)-T                                              HARM1840
ISN 0072          A(K1)=A(K1)+T                                              HARM1850
ISN 0073          T=A(K3+1)                                                  HARM1860
ISN 0074          A(K3+1)=A(K1+1)-T                                          HARM1870
ISN 0075          A(K1+1)=A(K1+1)+T                                          HARM1880
            C                                                                HARM1890
ISN 0076          T=A(K1)                                                    HARM1900
ISN 0077          A(K1)=A(K)-T                                               HARM1910
ISN 0078          A(K)=A(K)+T                                                HARM1920
ISN 0079          T=A(K1+1)                                                  HARM1930
ISN 0080          A(K1+1)=A(K+1)-T                                           HARM1940
ISN 0081          A(K+1)=A(K+1)+T                                            HARM1950
            C                                                                HARM1960
ISN 0082          R=-A(K3+1)                                                 HARM1970
ISN 0083          T = A(K3)                                                  HARM1980
ISN 0084          A(K3)=A(K2)-R                                              HARM1990
ISN 0085          A(K2)=A(K2)+R                                              HARM2000
ISN 0086          A(K3+1)=A(K2+1)-T                                          HARM2010
ISN 0087       80 A(K2+1)=A(K2+1)+T                                          HARM2020
ISN 0088          IF (JLAST) 235,235,82                                      HARM2030
ISN 0089       82 JJ=JJDIF   +1                                              HARM2040
            C                                                                HARM2050
            C     DO FOR J=1                                                 HARM2060
ISN 0090          ILAST= IL +JJ                                              HARM2070
ISN 0091          DO 85 I = JJ,ILAST,IDIF                                    HARM2080
ISN 0092          KLAST = KL+I                                               HARM2090
ISN 0093          DO 85 K=I,KLAST,2                                          HARM2100
ISN 0094          K1 = K+K3IT                                                HARM2110
ISN 0095          K2 = K1+KBIT                                               HARM2120
ISN 0096          K3 = K2+KBIT                                               HARM2130
            C                                                                HARM2140
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                C      LETTING W=(1+I)/ROOT2,W3=(-1+I)/ROOT2,W2=I,                HARM2150
                C      A(K)=A(K)+A(K2)*I                                          HARM2160
                C      A(K2)=A(K)-A(K2)*I                                         HARM2170
                C      A(K1)=A(K1)*W+A(K3)*W3                                     HARM2180
                C      A(K3)=A(K1)*W-A(K3)*W3                                     HARM2190
                C                                                                 HARM2200
                C      A(K)=A(K)+A(K1)                                            HARM2210
                C      A(K1)=A(K)-A(K1)                                           HARM2220
                C      A(K2)=A(K2)+A(K3)*I                                        HARM2230
                C      A(K3)=A(K2)-A(K3)*I                                        HARM2240
                C                                                                 HARM2250
ISN 0097               R =-A(K2+1)                                                HARM2260
ISN 0098               T = A(K2)                                                  HARM2270
ISN 0099               A(K2) = A(K)-R                                             HARM2280
ISN 0100               A(K) = A(K)+R                                              HARM2290
ISN 0101               A(K2+1)=A(K+1)-T                                           HARM2300
ISN 0102               A(K+1)=A(K+1)+T                                            HARM2310
                C                                                                 HARM2320
ISN 0103               AWR=A(K1)-A(K1+1)                                          HARM2330
ISN 0104               AWI = A(K1+1)+A(K1)                                        HARM2340
ISN 0105               R=-A(K3)-A(K3+1)                                           HARM2350
ISN 0106               T=A(K3)-A(K3+1)                                            HARM2360
ISN 0107               A(K3)=(AWR-R)/ROOT2                                        HARM2370
ISN 0108               A(K3+1)=(AWI-T)/ROOT2                                      HARM2380
ISN 0109               A(K1)=(AWR+R)/ROOT2                                        HARM2390
ISN 0110               A(K1+1)=(AWI+T)/ROOT2                                      HARM2400
ISN 0111               T= A(K1)                                                   HARM2410
ISN 0112               A(K1)=A(K)-T                                               HARM2420
ISN 0113               A(K)=A(K)+T                                                HARM2430
ISN 0114               T=A(K1+1)                                                  HARM2440
ISN 0115               A(K1+1)=A(K+1)-T                                           HARM2450
ISN 0116               A(K+1)=A(K+1)+T                                            HARM2460
ISN 0117               R=-A(K3+1)                                                 HARM2470
ISN 0118               T=A(K3)                                                    HARM2480
ISN 0119               A(K3)=A(K2)-R                                              HARM2490
ISN 0120               A(K2)=A(K2)+R                                              HARM2500
ISN 0121               A(K3+1)=A(K2+1)-T                                          HARM2510
ISN 0122            85 A(K2+1)=A(K2+1)+T                                          HARM2520
ISN 0123               IF(JLAST-1) 235,235,90                                     HARM2530
ISN 0124            90 JJ= JJ + JJDIF                                             HARM2540
                C                                                                 HARM2550
                C      NOW DO THE REMAINING J'S                                   HARM2560
ISN 0125               DO 230 J=2,JLAST                                           HARM2570
                C                                                                 HARM2580
                C      FETCH W'S                                                  HARM2590
                C      DEF- W=W**INV(J), W2=W**2, W3=W**3                         HARM2600
ISN 0126            96 I=INV(J+1)                                                 HARM2610
ISN 0127            98 IC=NT-I                                                    HARM2620
ISN 0128               W(1)=S(IC)                                                 HARM2630
ISN 0129               W(2)=S(I)                                                  HARM2640
ISN 0130               I2=2*I                                                     HARM2650
ISN 0131               I2C=NT-I2                                                  HARM2660
ISN 0132               IF(I2C)120,110,100                                         HARM2670
                C                                                                 HARM2680
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LEVEL 2.  (JUNE 78)            HARM            OS/360   FORTRAN H EXTENDED            DATE 80.19   21.57.09

                  C      2*I IS IN FIRST QUADRANT                                          HARM2690
 ISN 0133          100   W2(1)=S(I2C)                                                      HARM2700
 ISN 0134                W2(2)=S(I2)                                                       HARM2710
 ISN 0135                GO TO 130                                                         HARM2720
 ISN 0136          110   W2(1)=0.                                                          HARM2730
 ISN 0137                W2(2)=1.                                                          HARM2740
 ISN 0138                GO TO 130                                                         HARM2750
                  C                                                                        HARM2760
                  C      2*I IS IN SECOND QUADRANT                                         HARM2770
 ISN 0139          120   I2CC = I2C+NT                                                     HARM2780
 ISN 0140                I2C=-I2C                                                          HARM2790
 ISN 0141                W2(1)=-S(I2C)                                                     HARM2800
 ISN 0142                W2(2)=S(I2CC)                                                     HARM2810
 ISN 0143          130   I3=I+I2                                                           HARM2820
 ISN 0144                I3C=NT-I3                                                         HARM2830
 ISN 0145                IF(I3C)160,150,140                                                HARM2840
                  C                                                                        HARM2850
                  C      I3 IN FIRST QUADRANT                                              HARM2860
 ISN 0146          140   W3(1)=S(I3C)                                                      HARM2870
 ISN 0147                W3(2)=S(I3)                                                       HARM2880
 ISN 0148                GO TO 200                                                         HARM2890
 ISN 0149          150   W3(1)=0.                                                          HARM2900
 ISN 0150                W3(2)=1.                                                          HARM2910
 ISN 0151                GO TO 200                                                         HARM2920
                  C                                                                        HARM2930
 ISN 0152          160   I3CC=I3C+NT                                                       HARM2940
 ISN 0153                IF(I3CC)190,180,170                                               HARM2950
                  C                                                                        HARM2960
                  C      I3 IN SECOND QUADRANT                                             HARM2970
 ISN 0154          170   I3C=-I3C                                                          HARM2980
 ISN 0155                W3(1)=-S(I3C)                                                     HARM2990
 ISN 0156                W3(2)=S(I3CC)                                                     HARM3000
 ISN 0157                GO TO 200                                                         HARM3010
 ISN 0158          180   W3(1)=-1.                                                         HARM3020
 ISN 0159                W3(2)=0.                                                          HARM3030
 ISN 0160                GO TO 200                                                         HARM3040
                  C                                                                        HARM3050
                  C      3*I IN THIRD QUADRANT                                             HARM3060
 ISN 0161          190   I3CCC=NT+I3CC                                                     HARM3070
 ISN 0162                I3CC = -I3CC                                                      HARM3080
 ISN 0163                W3(1)=-S(I3CCC)                                                   HARM3090
 ISN 0164                W3(2)=-S(I3CC)                                                    HARM3100
 ISN 0165          200   ILAST=IL+JJ                                                       HARM3110
 ISN 0166                DO 220 I=JJ,ILAST,IDIF                                            HARM3120
 ISN 0167                KLAST=KL+I                                                        HARM3130
 ISN 0168                DO 220 K=I,KLAST,2                                                HARM3140
 ISN 0169                K1=K+K3IT                                                         HARM3150
 ISN 0170                K2=K1+KBIT                                                        HARM3160
 ISN 0171                K3=K2+KBIT                                                        HARM3170
                  C                                                                        HARM3180
                  C      DO TWO STEPS WITH J NOT 0                                         HARM3190
                  C      A(K)=A(K)+A(K2)*W2                                                HARM3200
                  C      A(K2)=A(K)-A(K2)*W2                                               HARM3210
                  C      A(K1)=A(K1)*W+A(K3)*W3                                            HARM3220
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LEVEL 2.3.0 (JUNE 78)             HARM           OS/360  FORTRAN H EXTENDED               DATE 80.195 21.57.09
                    C      A(K3)=A(K1)*W-A(K3)*W3                                                  HARM3230
                    C                                                                              HARM3240
                    C      A(K)=A(K)+A(K1)                                                         HARM3250
                    C      A(K1)=A(K)-A(K1)                                                        HARM3260
                    C      A(K2)=A(K2)+A(K3)*I                                                     HARM3270
                    C      A(K3)=A(K2)-A(K3)*I                                                     HARM3280
                    C                                                                              HARM3290
  ISN 0172                 R=A(K2)*W2(1)-A(K2+1)*W2(2)                                             HARM3300
  ISN 0173                 T=A(K2)*W2(2)+A(K2+1)*W2(1)                                             HARM3310
  ISN 0174                 A(K2)=A(K)-R                                                            HARM3320
  ISN 0175                 A(K)=A(K)+R                                                             HARM3330
  ISN 0176                 A(K2+1)=A(K+1)-T                                                        HARM3340
  ISN 0177                 A(K+1)=A(K+1)+T                                                         HARM3350
                    C                                                                              HARM3360
  ISN 0178                 R=A(K3)*W3(1)-A(K3+1)*W3(2)                                             HARM3370
  ISN 0179                 T=A(K3)*W3(2)+A(K3+1)*W3(1)                                             HARM3380
  ISN 0180                 AWR=A(K1)*W(1)-A(K1+1)*W(2)                                             HARM3390
  ISN 0181                 AWI=A(K1)*W(2)+A(K1+1)*W(1)                                             HARM3400
  ISN 0182                 A(K3)=AWR-R                                                             HARM3410
  ISN 0183                 A(K3+1)=AWI-T                                                           HARM3420
  ISN 0184                 A(K1)=AWR+R                                                             HARM3430
  ISN 0185                 A(K1+1)=AWI+T                                                           HARM3440
  ISN 0186                 T=A(K1)                                                                 HARM3450
  ISN 0187                 A(K1)=A(K)-T                                                            HARM3460
  ISN 0188                 A(K)=A(K)+T                                                             HARM3470
  ISN 0189                 T=A(K1+1)                                                               HARM3480
  ISN 0190                 A(K1+1)=A(K+1)-T                                                        HARM3490
  ISN 0191                 A(K+1)=A(K+1)+T                                                         HARM3500
  ISN 0192                 R=-A(K3+1)                                                              HARM3510
  ISN 0193                 T=A(K3)                                                                 HARM3520
  ISN 0194                 A(K3)=A(K2)-R                                                           HARM3530
  ISN 0195                 A(K2)=A(K2)+R                                                           HARM3540
  ISN 0196                 A(K3+1)=A(K2+1)-T                                                       HARM3550
  ISN 0197             220 A(K2+1)=A(K2+1)+T                                                       HARM3560
                    C      END OF I AND K LOOPS                                                    HARM3570
                    C                                                                              HARM3580
  ISN 0198             230 JJ=JJDIF+JJ                                                             HARM3590
                    C      END OF J-LOOP                                                           HARM3600
                    C                                                                              HARM3610
  ISN 0199             235 JLAST=4*JLAST+3                                                         HARM3620
  ISN 0200             240 CONTINUE                                                                HARM3630
                    C      END OF  L  LOOP                                                         HARM3640
                    C                                                                              HARM3650
  ISN 0201             250 CONTINUE                                                                HARM3660
                    C      END OF  ID  LOOP                                                        HARM3670
                    C                                                                              HARM3680
                    C      WE NOW HAVE THE COMPLEX FOURIER SUMS BUT THEIR ADDRESSES ARE            HARM3690
                    C      BIT-REVERSED.  THE FOLLOWING ROUTINE PUTS THEM IN ORDER                 HARM3700
  ISN 0202                 NTSQ=NT*NT                                                              HARM3710
  ISN 0203                 M3MT=M3-MT                                                              HARM3720
  ISN 0204             350 IF(M3MT) 370,360,360                                                    HARM3730
                    C                                                                              HARM3740
                    C      M3 GR. OR EQ. MT                                                        HARM3750
  ISN 0205             360 IGO3=1                                                                  HARM3760
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ISN 0206              N3VNT=N3/NT                                          HARM3770
ISN 0207              MINN3=NT                                             HARM3780
ISN 0208              GO TO 380                                            HARM3790
            C                                                              HARM3800
            C         N3 LESS THAN MT                                      HARM3810
ISN 0209        370   IGO3=2                                               HARM3820
ISN 0210              N3VNT=1                                              HARM3830
ISN 0211              NTVN3=NT/N3                                          HARM3840
ISN 0212              MINN3=N3                                             HARM3850
ISN 0213        380   JJD3 = NTSQ/N3                                       HARM3860
ISN 0214              M2MT=M2-MT                                           HARM3870
ISN 0215        450   IF (M2MT)470,460,460                                 HARM3880
            C                                                              HARM3890
            C         M2 GR. OR EQ. MT                                     HARM3900
ISN 0216        460   IGO2=1                                               HARM3910
ISN 0217              N2VNT=N2/NT                                          HARM3920
ISN 0218              MINN2=NT                                             HARM3930
ISN 0219              GO TO 480                                            HARM3940
            C                                                              HARM3950
            C         M2 LESS THAN MT                                      HARM3960
ISN 0220        470   IGO2 = 2                                             HARM3970
ISN 0221              N2VNT=1                                              HARM3980
ISN 0222              NTVN2=NT/N2                                          HARM3990
ISN 0223              MINN2=N2                                             HARM4000
ISN 0224        480   JJD2=NTSQ/N2                                         HARM4010
ISN 0225              M1MT=M1-MT                                           HARM4020
ISN 0226        550   IF(M1MT)570,560,560                                  HARM4030
            C                                                              HARM4040
            C         M1 GR. OR EQ. MT                                     HARM4050
ISN 0227        560   IGO1=1                                               HARM4060
ISN 0228              N1VNT=N1/NT                                          HARM4070
ISN 0229              MINN1=NT                                             HARM4080
ISN 0230              GO TO 580                                            HARM4090
            C                                                              HARM4100
            C         M1 LESS THAN MT                                      HARM4110
ISN 0231        570   IGO1=2                                               HARM4120
ISN 0232              N1VNT=1                                              HARM4130
ISN 0233              NTVN1=NT/N1                                          HARM4140
ISN 0234              MINN1=N1                                             HARM4150
ISN 0235        580   JJD1=NTSQ/N1                                         HARM4160
ISN 0236        600   JJ3=1                                                HARM4170
ISN 0237              J=1                                                  HARM4180
ISN 0238              DO 890 JPP3=1,N3VNT                                  HARM4190
ISN 0239              IPP3=INV(JJ3)                                        HARM4200
ISN 0240              DO 870 JP3=1,MINN3                                   HARM4210
ISN 0241              GO TO (610,620),IGO3                                 HARM4220
ISN 0242        610   IP3=INV(JP3)*N3VNT                                   HARM4230
ISN 0243              GO TO 630                                            HARM4240
ISN 0244        620   IP3=INV(JP3)/NTVN3                                   HARM4250
ISN 0245        630   I3=(IPP3+IP3)*N2                                     HARM4260
ISN 0246        700   JJ2=1                                                HARM4270
ISN 0247              DO 870 JPP2=1,N2VNT                                  HARM4280
ISN 0248              IPP2=INV(JJ2)+I3                                     HARM4290
ISN 0249              DO 850 JP2=1,MINN2                                   HARM4300
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ISN 0250            GO TO (710,720),IGO2                                   HARM4310
ISN 0251        710 IP2=INV(JP2)*N2VNT                                     HARM4320
ISN 0252            GO TO 730                                              HARM4330
ISN 0253        720 IP2=INV(JP2)/N(VN2                                     HARM4340
ISN 0254        730 I2=(IPP2+IP2)*N1                                       HARM4350
ISN 0255        800 JJ1=1                                                  HARM4360
ISN 0256            DO 850 JPP1=1,NIVNT                                    HARM4370
ISN 0257            IPP1=INV(JJ1)+I2                                       HARM4380
ISN 0258            DO 850 JP1=1,MINN1                                     HARM4390
ISN 0259            GO TO (810,820),IGO1                                   HARM4400
ISN 0260        810 IP1=INV(JP1)*NIVNT                                     HARM4410
ISN 0261            GO TO 830                                              HARM4420
ISN 0262        820 IP1=INV(JP1)/NTVN1                                     HARM4430
ISN 0263        830 I=2*(IPP1+IP1)+1                                       HARM4440
ISN 0264            IF (J-I) 840,850,850                                   HARM4450
ISN 0265        840 T=A(I)                                                 HARM4460
ISN 0266            A(I)=A(J)                                              HARM4470
ISN 0267            A(J)=T                                                 HARM4480
ISN 0268            T=A(I+1)                                               HARM4490
ISN 0269            A(I+1)=A(J+1)                                          HARM4500
ISN 0270            A(J+1)=T                                               HARM4510
ISN 0271        850 J=J+2                                                  HARM4530
ISN 0272        860 JJ1=JJ1+JJD1                                           HARM4540
              C     END OF JPP1 AND JP2                                    HARM4550
              C                                                            HARM4560
ISN 0273        870 JJ2=JJ2+JJD2                                           HARM4570
              C     END OF JPP2 AND JP3 LOOPS                              HARM4580
              C                                                            HARM4590
ISN 0274        880 JJ3 = JJ3+JJD3                                         HARM4600
              C     END OF JPP3 LOOP                                       HARM4610
              C                                                            HARM4620
ISN 0275        890 IF(IFSET)891,895,895                                   HARM4630
ISN 0276        891 DO 892 I = 1,NX                                        HARM4640
ISN 0277        892 A(2*I) = -A(2*I)                                       HARM4650
ISN 0278        895 RETURN                                                 HARM4660
              C                                                            HARM4670
              C     THE FOLLOWING PROGRAM COMPUTES THE SIN AND INV TABLES. HARM4680
              C                                                            HARM4690
ISN 0279        900 MT=MAX0(M(1),M(2),M(3)) -2                             HARM4700
ISN 0280            MT = MAX0(2,MT)                                        HARM4710
ISN 0281        904 IF (MT-18) 906,906,13                                  HARM4720
ISN 0282        906 IFERR=0                                                HARM4750
ISN 0283            NT=2**MT                                               HARM4760
ISN 0284            NTV2=NT/2                                              HARM4770
              C                                                            HARM4780
              C     SET UP SIN TABLE                                       HARM4790
              C     THETA=PIE/2**(L+1) FOR L=1                             HARM4800
ISN 0285        910 THETA=.7853981634                                      HARM4810
              C                                                            HARM4820
              C     JSTEP=2**(MT-L+1) FOR L=1                              HARM4830
ISN 0286            JSTEP=NT                                               HARM4840
              C                                                            HARM4850
              C     JDIF=2**(MT-L) FOR L=1                                 HARM4860
ISN 0287            JDIF=NTV2                                              HARM4880
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LEVEL 2.3.. (JUNE 78)          HARM          OS/360    FORTRAN H EXTENDED          DATE 80.199   .57.09

  ISN 0288          S(JDIF)=SIN(THETA)                                          HARM4890
  ISN 0289          DO 950 L=2,MT                                               HARM4900
  ISN 0290          THETA=THETA/2.                                              HARM4910
  ISN 0291          JSTEP2=JSTEP                                                HARM4920
  ISN 0292          JSTEP=JDIF                                                  HARM4930
  ISN 0293          JDIF=JSTEP/2                                                HARM4940
  ISN 0294          S(JDIF)=SIN(THETA)                                          HARM4950
  ISN 0295          JC1=NT-JDIF                                                 HARM4960
  ISN 0296          S(JC1)=COS(THETA)                                           HARM4970
  ISN 0297          JLAST=NT-JSTEP2                                             HARM4980
  ISN 0298          IF(JLAST - JSTEP) 950,920,920                               HARM4990
  ISN 0299      920 DO 940 J=JSTEP,JLAST,JSTEP                                  HARM5000
  ISN 0300          JC=NT-J                                                     HARM5010
  ISN 0301          JD=J+JDIF                                                   HARM5020
  ISN 0302      940 S(JD)=S(J)*S(JC1)+S(JDIF)*S(JC)                             HARM5030
  ISN 0303      950 CONTINUE                                                    HARM5040
             C                                                                  HARM5050
             C      SET UP INV(J) TABLE                                         HARM5060
             C                                                                  HARM5070
  ISN 0304      960 MTLEXP=NTV2                                                 HARM5080
             C                                                                  HARM5090
             C      MTLEXP=2**(MT-L). FOR L=1                                   HARM5100
  ISN 0305          LM1EXP=1                                                    HARM5110
             C                                                                  HARM5120
             C      LM1EXP=2**(L-1). FOR L=1                                    HARM5130
  ISN 0306          INV(1)=0                                                    HARM5140
  ISN 0307          DO 980 L=1,MT                                               HARM5150
  ISN 0308          INV(LM1EXP+1) = MTLEXP                                      HARM5160
  ISN 0309          DO 970 J=2,LM1EXP                                           HARM5170
  ISN 0310          JJ=J+LM1EXP                                                 HARM5180
  ISN 0311      970 INV(JJ)=INV(J)+MTLEXP                                       HARM5190
  ISN 0312          MTLEXP=MTLEXP/2                                             HARM5200
  ISN 0313      980 LM1EXP=LM1EXP*2                                             HARM5210
  ISN 0314      982 IF(IFSET)12,895,12                                          HARM5220
  ISN 0315          END                                                         HARM5230

*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(2) LINECOUNT(55) SIZE(MAX) AUTODBL(NONE)

*OPTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF ALC NOANSF NOTERM IBM FL/

*STATISTICS*     SOURCE STATEMENTS =      314, PROGRAM SIZE =      5206, SUBPROGRAM NAME =  HARM

*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                                    56K BYTES OF CORE NOT USED
```

```
LEVEL 2.3.  (JUNE 73)                    OS/360    ,RTRAN H EXTENDED              DATE 80.199,  .57.13

REQUESTED OPTIONS:

OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(2) LINECOUNT(56) SIZE(MAX) AUTODBL(NONE)
                   SOURCE EBCDIC NOLIST NODECK OBJECT NJMAP NOFORMAT GOSTMT NOXREF ALC NOANSF NOTERM IBM FL/

  ISN 0002              SUBROUTINE GREYSC(IFILE1,NLEVEL,AMAT,IDIM,JDIM,IMIN,IMAX,IDEL,
                       *  JMIN,JMAX,JDEL,AMIN,AMAX,TITLE,NCHAR)
               C        LEVEL 2,AMAT
  ISN 0003              DIMENSION ICHARS(10,3),LINE(132,3),LEVEL(10),AMAT(IDIM,JDIM)
  ISN 0004              DIMENSION TITLE(20)
  ISN 0005              DOUBLE PRECISION TITLE
  ISN 0006              DATA ICHARS/1H ,1H.,1H-,1H+,1H*,1H#,1H*,3*1HO
                       * ,6*1H ,1HX,1H*,2*1H#,9*1H ,1H*/
  ISN 0007              DATA IBORDR/1H*/,IBLANK/1H /
  ISN 0008              DATA LEVEL/6*1,3*2,3/
  ISN 0009              DATA NCPW/10/
               C        DATA NLMAX/59/
  ISN 0010              IFILEX=-IFILE1
               C
               C        SCALE, IF NECESSARY
               C
  ISN 0011              AMX=AMAX
  ISN 0012              IFILE=IABS(IFILEX)
  ISN 0013              AMN=AMIN
  ISN 0014              IF(AMAX.GT.AMIN) GO TO 100
  ISN 0016              AMN=1.E20
  ISN 0017              AMX=-1.E20
  ISN 0018              DO 50 I=IMIN,IMAX,IDEL
  ISN 0019              DO 50 J=JMIN,JMAX,JDEL
  ISN 0020              AMN=AMIN1(AMN,AMAT(I,J))
  ISN 0021       50     AMX=AMAX1(AMX,AMAT(I,J))
  ISN 0022      100     CONTINUE
               C
               C        PRINT HEADER
               C
  ISN 0023              NWORDS=(NCHAR-1)/NCPW+1
  ISN 0024              IF(NCPW.EQ.6) WRITE(IFILE,1040) (TITLE(I),I=1,NWORDS)
  ISN 0026              IF(NCPW.EQ.4) WRITE(IFILE,1041) (TITLE(I),I=1,NWORDS)
  ISN 0028              IF(NCPW.EQ.10) WRITE(IFILE,1042) (TITLE(I),I=1,NWORDS)
  ISN 0030              IF(NCPW.EQ.5) WRITE(IFILE,1043) (TITLE(I),I=1,NWORDS)
  ISN 0032              IF(AMX.EQ.AMN)  RETURN
               C
               C         PREPARE A LINE FOR PRINTING
               C
  ISN 0034              LINE(1,1)=IBORDR
  ISN 0035              JLOC=(JMAX-JMIN)/JDEL+3
  ISN 0036              LINE(JLOC+2,1)=IBORDR
  ISN 0037              LINE(1,2)=IBLANK
  ISN 0038              LINE(1,3)=IBLANK
  ISN 0039              LINE(JLOC+2,2)=IBLANK
  ISN 0040              LINE(JLOC+2,3)=IBLANK
  ISN 0041              LASTLI=JLOC+2
  ISN 0042              NLASTL=LASTLI-1
  ISN 0043              WRITE(IFILE,1045) (IBORDR,I=1,LASTLI)
```

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LEVEL 2.3.0 (JUNE 78)          GREYSC          OS/360   FORTRAN H EXTENDED          DATE 80.199/  .57.13

ISN 0044            DO 400 I=IMIN,IMAX,IDEL
ISN 0045            DO 250 II=1,3
ISN 0046            DO 250 J=2,NLASTL
ISN 0047       250  LINE(J,II)=IBLANK
ISN 0048            LEV=1
ISN 0049            J=2
ISN 0050            DO 300 JJ=JMIN,JMAX,JDEL
ISN 0051            J=J+1
ISN 0052            L=(AMAT(I,JJ)-AMN)/(AMX-AMN)*FLOAT(NLEVEL)+1.
ISN 0053            L=MAX0(1,L)
ISN 0054            L=MIN0(NLEVEL,L)
ISN 0055            LEV=MAX0(LEV,LEVEL(L))
ISN 0056            LEVNOW=LEVEL(L)
ISN 0057            DO 300 K=1,LEVNOW
ISN 0058            LINE(J,K)=ICHARS(L,K)
ISN 0059       300  CONTINUE
              C
              C       FIND LAST PRINT POSITION
              C
ISN 0060            DO 400 KL=1,LEV
ISN 0061            DO 350 K=1,LASTLI
ISN 0062            KK=LASTLI-K+1
ISN 0063            IF(LINE(KK,KL).NE.IBLANK) GO TO 375
ISN 0065       350  CONTINUE
ISN 0066       375  CONTINUE
ISN 0067            IF(IFILEX.GT.0.AND.KL.EQ.LEV) WRITE(IFILE,1050) (LINE(II,KL),
                   1II=1,KK)
ISN 0069            IF(IFILEX.LT.0.AND.KL.EQ.1) WRITE(IFILE,1050) (LINE(II,KL),
                   1II=1,KK)
ISN 0071            IF(IFILEX.GT.0.AND.KL.NE.LEV) WRITE(IFILE,1060) (LINE(II,KL),
                   1II=1,KK)
ISN 0073            IF(IFILEX.LT.0.AND.KL.NE.1) WRITE(IFILE,1060)  (LINE(II,KL),
                   1II=1,KK)
ISN 0075       400  CONTINUE
              C
              C       WRITE LAST LINE (BORDER)
              C
ISN 0076            WRITE(IFILE,1070) (IBORDR,I=1,LASTLI)
              C
              C       PRINT TRAILING SCALE INFORMATION
              C
ISN 0077            IF(NCPW.EQ.6) WRITE(IFILE,1000) (TITLE(I),I=1,NWORDS)
ISN 0079            IF(NCPW.EQ.4) WRITE(IFILE,1001) (TITLE(I),I=1,NWORDS)
ISN 0081            IF(NCPW.EQ.10) WRITE(IFILE,1002) (TITLE(I),I=1,NWORDS)
ISN 0083            IF(NCPW.EQ.5) WRITE(IFILE,1003) (TITLE(I),I=1,NWORDS)
ISN 0085            WRITE(IFILE,1010)
ISN 0086            DELTA=(AMX-AMN)/FLOAT(NLEVEL)
ISN 0087            DO 200 I=1,NLEVEL
ISN 0088            XMIN=FLOAT(I-1)/FLOAT(NLEVEL)*(AMX-AMN)+AMN
ISN 0089            XMAX=XMIN+DELTA
ISN 0090            LEV=LEVEL(I)
ISN 0091            DO 175 J=1,LEV
ISN 0092            IF(IFILEX.GT.0.AND.J.EQ.LEV) WRITE(IFILE,1020) ICHARS(I,J),XMIN,
                   1 XMAX
```

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LEVEL 2.3.. (JUNE 78)          GREYSC          OS/360   FORTRAN H EXTENDED          DATE 80.199   1.57.13

  ISN 0094              IF(IFILEX.LT.0.AND.J.EQ.1) WRITE(IFILE,1020) ICHARS(I,J),XMIN,
                       1 XMAX
  ISN 0096              IF(IFILEX.GT.0.AND.J.NE.LEV) WRITE(IFILE,1030) ICHARS(I,J)
  ISN 0098              IF(IFILEX.LT.0.AND.J.NE.1) WRITE(IFILE,1030) ICHARS(I,J)
  ISN 0100        175   CONTINUE
  ISN 0101        200   CONTINUE
  ISN 0102              RETURN
  ISN 0103       1000   FORMAT(1H0,20A5)
  ISN 0104       1001   FORMAT(1H0,20A4)
  ISN 0105       1002   FORMAT(1H0,12A10)
  ISN 0106       1003   FORMAT(1H0,24A5)
  ISN 0107       1010   FORMAT(1H0,32HGREY-SCALE CHARACTERS AND RANGES/1X)
  ISN 0108       1020   FORMAT(5X,A1,5X,E15.6,5X,E15.6)
  ISN 0109       1030   FORMAT(1H+,      4X,A1)
  ISN 0110       1039   FORMAT(1H1)
  ISN 0111       1040   FORMAT(1H1/1X,20A6)
  ISN 0112       1041   FORMAT(1H1/1X,20A4)
  ISN 0113       1042   FORMAT(1H1/1X,12A10)
  ISN 0114       1043   FORMAT(1H1/1X,24A5)
  ISN 0115       1045   FORMAT(1H0,132A1)
  ISN 0116       1050   FORMAT(1X,132A1)
  ISN 0117       1060   FORMAT(1H+,      132A1)
  ISN 0118       1070   FORMAT(1X,132A1)
  ISN 0119              END

*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(2) LINECOUNT(55) SIZE(MAX) AUTODBL(NONE)

*OPTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF ALC NOANSF NOTERM IBM FLA

*STATISTICS*     SOURCE STATEMENTS =      118, PROGRAM SIZE =      4840, SUBPROGRAM NAME =GREYSC

*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                                    80K BYTES OF CORE NOT USED
```

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LEVEL 2.3.. (JUNE 78)                    OS/360    FORTRAN H EXTENDED            DATE 80.199   1.57.15

REQUESTED OPTIONS:

OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(2) LINECOUNT(55) SIZE(MAX) AUTODBL(NONE)
                   SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF ALC NOANSF NOTERM IBM FLA

  ISN 0002          SUBROUTINE PRNTER(ISTEP)                                                PRNTER
  ISN 0003          COMMON /LCM2/REFNDX(16384),SN(128),CS(128),ZTSQ(128),PQSQ(128)          LCM2
                   * ,AMPARY(16384),RADARY(16384)                                            LCM2
            C       LEVEL 2,REFNDX,SN,CS,ZTSQ,PQSQ,AMPARY,RADARY                             LCM2
  ISN 0004          COMMON  /ARRAYS/V(32768)                                                 ARRAYS
  ISN 0005          COMMON /PARAM/DZINC,MESH,LAMBDA,RO,FR,NQ,PCORP,OUTRAD,DX,NSTEPS,         PARAM
                   * NDZINC,MESHSQ,MSHSQ2,PI,WAVENM,DXSI,MS,NS,MF,NF,MSHPTS                  PARAM
  ISN 0006          COMMON /PRNTPL/PGREY,PWAIST,PLTWST,PLTMAX,LAST,IOUT,IGREY                PRNTPLT
                   * ,PLTFLD,PLTFLE                                                          PRNTPLT
            C       DIMENSION X(130),XWAIST(100),YWAIST(100),VRAD(100),WSTID(2),              PRNTER
            C      * MAXID(2),MAXX(2),MAXY(2),WSTX(2),WSTY(2),XT(100)                        PRNTER
            C       DIMENSION FIELDA(130),XID(2),FLDID(2),FLDTTL(2)                           PRNTER
            C       EQUIVALENCE (MAXX,WSTX)                                                  PRNTER
  ISN 0007          LOGICAL PGREY,PWAIST,PLTWST,PLTMAX,PLTFLD,PLTFLE,LAST                     PRNTER
  ISN 0008          REAL LAMBDA                                                              PRNTER
            C       DATA WSTID/19H2ND MOMENTS VS DIST/                                       PRNTER
            C       DATA MAXID/18HPEAK IRRAD VS DIST/                                        PRNTER
            C       DATA MAXX/10HAXIAL DIST/                                                 PRNTER
            C       DATA MAXY/15HPEAK IRRADIANCE/                                            PRNTER
            C       DATA WSTY/17HBEAM WAIST RATIOS/                                          PRNTER
            C       DATA XID/18HRADIAL DIST (MICR)/                                          PRNTER
            C       DATA FLDID/10HIRRADIANCE/                                                PRNTER
            C       DATA FLDTTL/20HIRRAD VS RADIAL DIST/                                     PRNTER
  ISN 0009          KSTEP=ISTEP+1                                                            PRNTER
  ISN 0010          IF(PGREY.OR.PWAIST) WRITE(IOUT,2000) ISTEP                               PRNTER
  ISN 0012          IF(PGREY.OR.PWAIST.OR.PLTMAX.OR.PLTWST) CALL PEAK(VMAX)                  PRNTER
  ISN 0014          IF(.NOT.(PWAIST.OR.PLTWST)) GO TO 10                                     PRNTER
  ISN 0016          CALL SIZE(RADARY,MESH,MESH,XO,YO,X2,Y2)                                  PRNTER
  ISN 0017          X2=1.4142135*X2*DX                                                       PRNTER
  ISN 0018          Y2=1.4142135*Y2*DX                                                       PRNTER
  ISN 0019          IF(PWAIST) WRITE(IOUT,2010) X2,Y2                                        PRNTER
  ISN 0021     2000 FORMAT(//,14H THIS IS STEP ,I2,/)                                        PRNTER
  ISN 0022     2010 FORMAT(/,38H BEAM WAIST IN X AND Y DIRECTIONS IS   ,2(F10.5,2X),          PRNTER
                   * 7HMICRONS)                                                              PRNTER
  ISN 0023       10 CONTINUE                                                                 PRNTER
  ISN 0024          IF(PGREY) CALL GREYSC(IGREY,10,RADARY,MESH,MESH,MS,MF,1,NS,NF,1,          PRNTER
                   * 0.,0.,10HIRRADIANCE,10)                                                 PRNTER
  ISN 0026          RETURN                                                                   PRNTER
  ISN 0027          END                                                                      PRNTER

*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(2) LINECOUNT(56) SIZE(MAX) AUTODBL(NONE)

*OPTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF ALC NOANSF NOTERM IBM F

*STATISTICS*     SOURCE STATEMENTS =       26, PROGRAM SIZE =       692, SUBPROGRAM NAME =PRNTER

*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                              112K BYTES OF CORE NOT USED
```

LEVEL 2.3.0 (JUNE 78) OS/360 FORTRAN H EXTENDED DATE 80.194 21.57.15

STATISTICS NO DIAGNOSTICS THIS STEP

```
IEF142I - STEP EXECUTED - COND CODE 0000
IEF285I   SYS1.FORTRAN                                          PASSED
IEF285I   VOL SER NOS= ACS002.
IEF285I   SYS80199.T215654.RV000.SBI404F2.LOADSET               PASSED
IEF285I   VOL SER NOS= SYSDA1.
IEF285I   SYS80199.T215654.RV000.SBI404F2.R0000001              DELETED
IEF285I   VOL SER NOS= SYSDA3.
IEF285I   SYS80199.T215654.RV000.SBI404F2.R0000002              DELETED
IEF285I   VOL SER NOS= SYSDA2.
IEF285I   SYS80199.T215654.SV000.SBI404F2.R0000003              SYSOUT
IEF285I   VOL SER NOS= SYSDA3.
IEF285I   SYS80199.T215654.RV000.SBI404F2.S0000004              SYSIN
IEF285I   VOL SER NOS= SYSDA2.
IEF285I   SYS80199.T215654.RV000.SBI404F2.S0000004              DELETED
IEF285I   VOL SER NOS= SYSDA2.

CCN301I   SYSPRINT PRINTED    24 TOTAL PAGES. REQUIRED    10 TRACKS.

  REGION ALLOCATION        CORE USED
        250K                  250K

   STEP CPU TIME          JOB CPU TIME        STEP I/O COUNT       JOB I/O COUNT
        3.14S                 3.14S                 306                 306

XXGO      EXEC PGM=&LOADER,COND=(5,LT,FORT),TIME=&TG,REGION=&RG              00000320
IEF653I SUBSTITUTION JCL - PGM=LOADER,COND=(5,LT,FORT),TIME=1439,REGION=450K
XXFT05F001 DD DDNAME=SYSIN                                                    00000340
XXSTEPLIB  DD DISP=(SHR,PASS),DSN=$YS&LEVEL..FORTRAN                          00000360
IEF653I SUBSTITUTION JCL - DISP=(SHR,PASS),DSN=$YS1.FORTRAN
XXSYSLIB   DD DISP=(SHR,PASS),DSN=$YS&LEVEL..FORTLIB                          00000380
IEF653I SUBSTITUTION JCL - DISP=(SHR,PASS),DSN=$YS1.FORTLIB
XXSYSLIN   DD DSN=&&LOADSET,DISP=(OLD,DELETE)                                 00000400
XXSYSPROUT DD SYSOUT=A,SPACE=(133,(200,75),RLSE)                              00000420
XXFT06F001 DD SYSOUT=A,UNIT=SYSOUT,SPACE=(TRK,&PG,RLSE),                      00000440
IEF653I SUBSTITUTION JCL - SYSOUT=A,UNIT=SYSOUT,SPACE=(TRK,25,RLSE),
XX           DCB=(RECFM=FBA,LRECL=133,BLKSIZE=4123)                           00000460
//GO.SYSIN  DD  *
//
IEF236I ALLOC. FOR SBI404F2 GO
IEF237I 153    ALLOCATED TO FT05F001
IEF237I 822    ALLOCATED TO STEPLIB
IEF237I 822    ALLOCATED TO SYSLIB
IEF237I 153    ALLOCATED TO SYSLIN
IEF237I 713    ALLOCATED TO SYSPROUT
IEF237I 265    ALLOCATED TO FT06F001
```

) . 360 LOADER

OPTIONS USED - PRINT,MAP,NOLET,CALL,RES,NOTERM,SIZE=635224,NAME=**GO

NAME	TYPE	ADDR	NAME	TYPE	ADDR	NAME	TYPE	ADDR	NAME	TYPE	ADDR	NAME
MAIN	SD	116010	PEAK	SD	1174D8	SIZE	SD	1176F8	ARRAYS	SD	117410	PARAM
PRNTPL	SD	137A68	HARM	SD	137A90	GREYSC	SD	138EE8	PRNTER	SD	13A1D0	IHOFIXPI *
FIXPI# *	LR	13A488	IHOECOMH*	SD	13A5D8	I80B1971*	LR	13A604	I3COM# *	LR	13A604	FOIOCS# *
INTSWTCH*	LR	13B3C0	FIOAP# *	SD	13B488	AP0B1971*	LR	13B9FC	IHOCOM42*	SD	13B9B0	SEQDASD *
IHOFCVTH*	SD	13C548	ADCON# *	LR	13C548	FCVAOUTP*	LR	13C5F2	FCVLOUTP*	LR	13C682	FCVZOUTP*
FCVIOUTP*	LR	13CBBA	FCVEOUTP*	LR	13CCAA	FCVCOUTP*	LR	13CCAA	INT6SWCH*	LR	13CF0C	IHOEFNTH*
ARITH# *	LR	13CF90	ADJSWTCH*	LR	13D524	IHOEFIOS*	SD	13D790	FIOCS# *	LR	13D790	FIOCS3EP*
IHOFIOS2*	SD	13F920	IHOFCONI*	SD	13EF68	FOCONI# *	LR	13EF68	IHOFCONO*	SD	13F268	FOCONO# *
IHOERRM *	SD	13F730	ERRMON *	LR	13F730	IHOERRE *	LR	13F748	IHOFTEN *	SD	13F258	FTEN# *
IHOETRCH*	SD	13FEF0	IHOTRCH *	LR	13FEF0	ERRTRA *	LR	13FEF8	IHOUOPT *	SD	1401A0	IHOUATBL*
IHONAMEL*	SD	140C10	FRDNL# *	LR	140C10	FWRNL# *	LR	14130C	IHOFRXPI*	SD	141BA8	FRXPI# *
IHOSSQRT*	SD	141428	SQRT *	LR	141A28	IHSSQRT *	LR	141A28	IHOSSCN *	SD	141390	COS *
IHS$COS *	LR	141B90	SIN *	LR	141BB2	IHS$SIN *	LR	141BB2	IHOSEXP *	SD	141098	IHS$EXP *
EXP *	LR	141098	LCM2	CM	141F48							

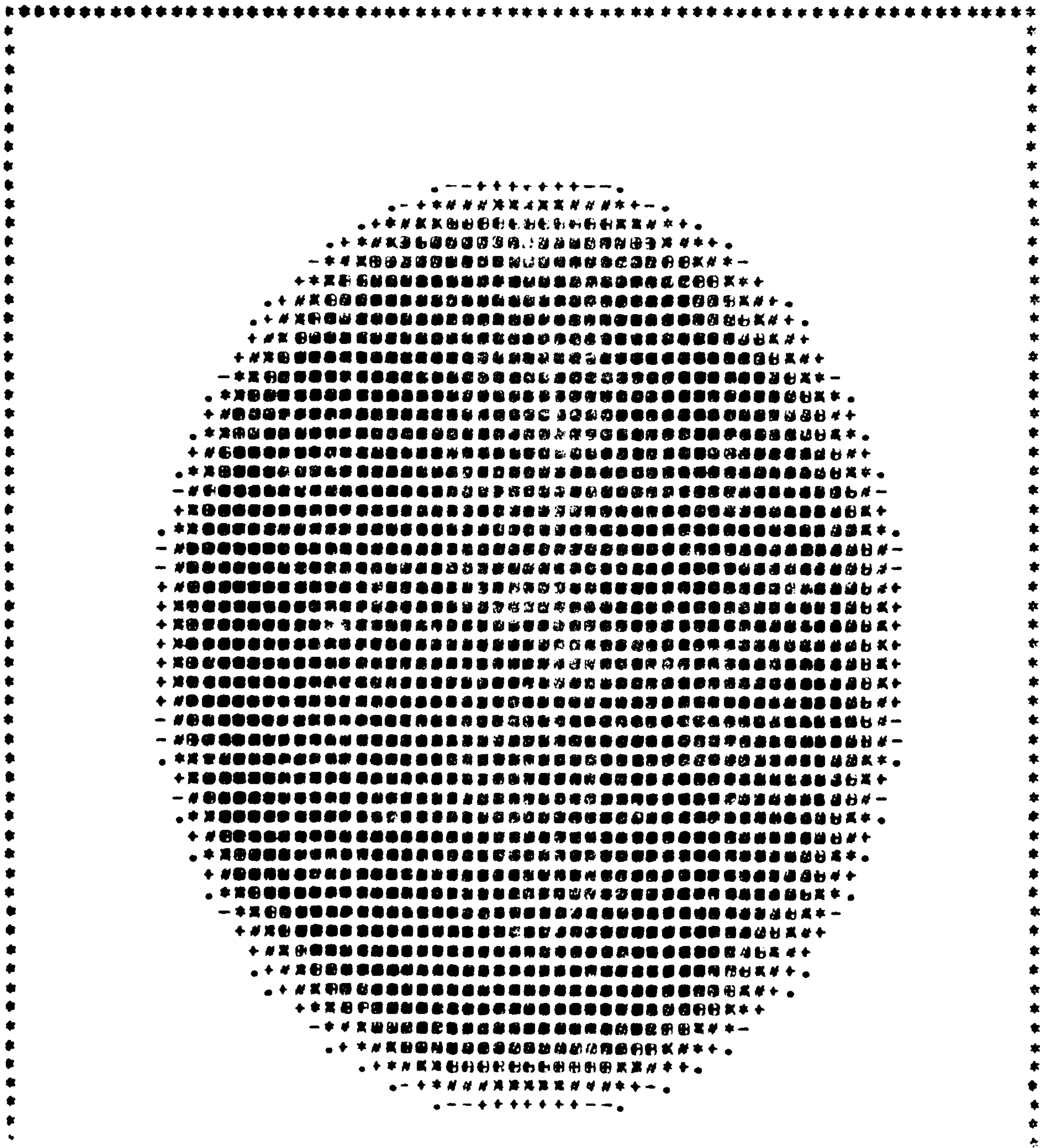
TOTAL LENGTH 5C738
ENTRY ADDRESS 116010

```
 1
 0.0  0.0
 1
 0.0  0.0
      1.40000
25.0
&DFAULT
LAMBDA=  .800000012      ,RO=  20.0000000      ,NO=  1.47399954     ,PCOR2=  1.39999952     ,OUTRAD=  62.0000000
NSTEPS=             40,NDZINC=              5,IOUT=              5,I,REV=              6,PGREY=T,PWAIST=T,PLTWST=F,PLTMAX=F,
       128 = MESH                                   DX = 1.0
&END

ZMIN  =   234.6827 MICRONS
DZINC =     46.9365 MICRONS
RN2ND =   0.448E-04 MICRONS**(-2)
ALPHA =     0.03213
```

P-10 STUDY

REFNDX



```
*                                                                                          .
*                                                                                          *
*                                                                                          *
*                                                                                          *
************************************************************    ************
```

REFNDX

GREY-SCALE CHARACTERS AND RANGES

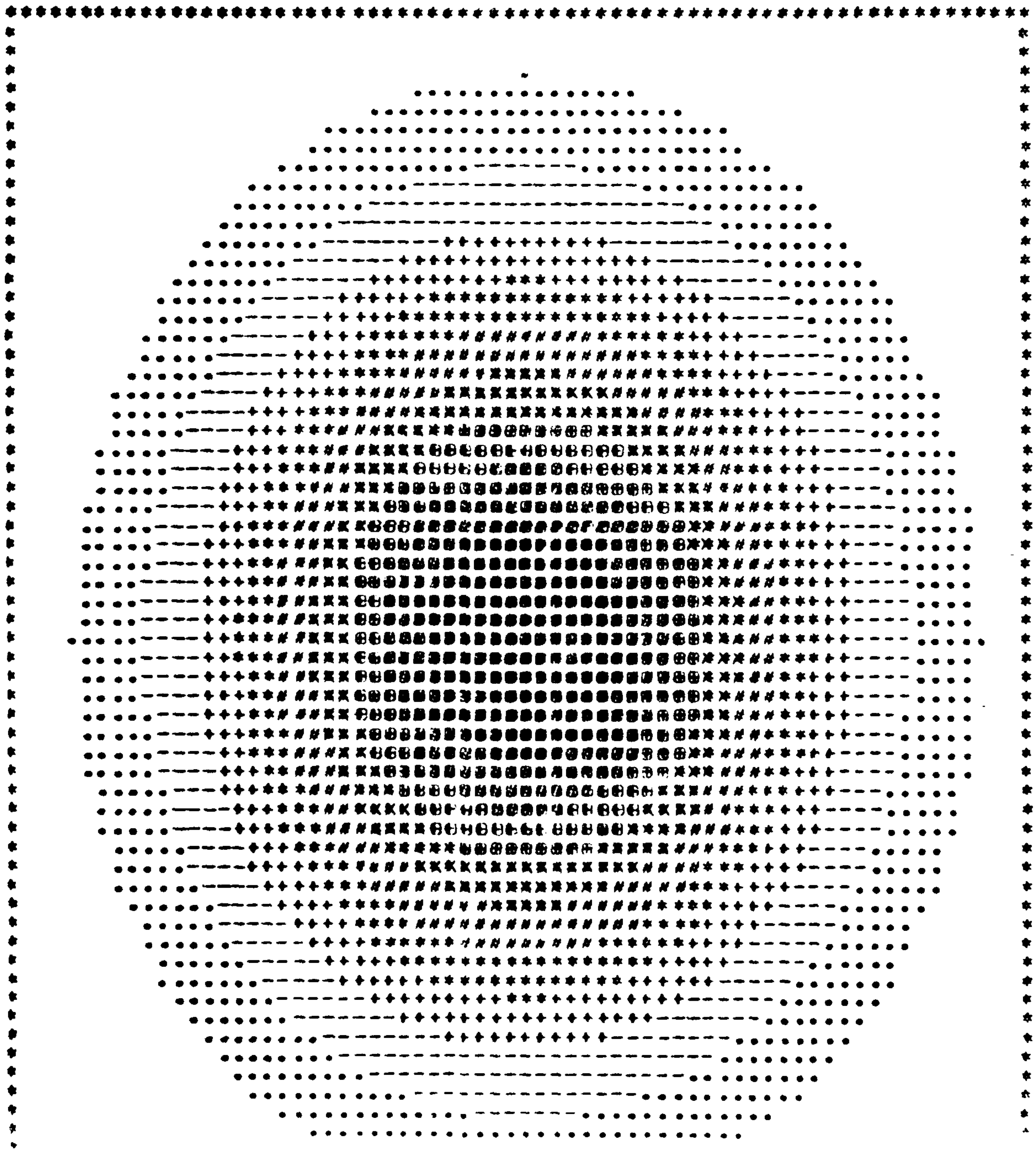
	0.145928E+01	0.146135E+01
.	0.146135E+01	0.146342E+01
-	0.146342E+01	0.146549E+01
+	0.146550E+01	0.146757E+01
*	0.146757E+01	0.146964E+01
#	0.146964E+01	0.147171E+01
[illegible]	0.147171E+01	0.147378E+01
[illegible]	0.147378E+01	0.147585E+01
[illegible]	0.147585E+01	0.147793E+01
[illegible]	0.147793E+01	0.148000E+01

THIS IS STEP 0

SUML = 0.4860770E+00   SUMR = 0.5139230E+00

BEAM WAIST IN X AND Y DIRECTIONS IS   19.99481   19.99631 MICRONS

IRRADIAN



```
*                         .....................                         *
*                            ...............                            *
*                                  .                                    *
*                                                                       *
**********  **************************************************  *************
```

IRRADIAN

GREY-SCALE CHARACTERS AND RANGES

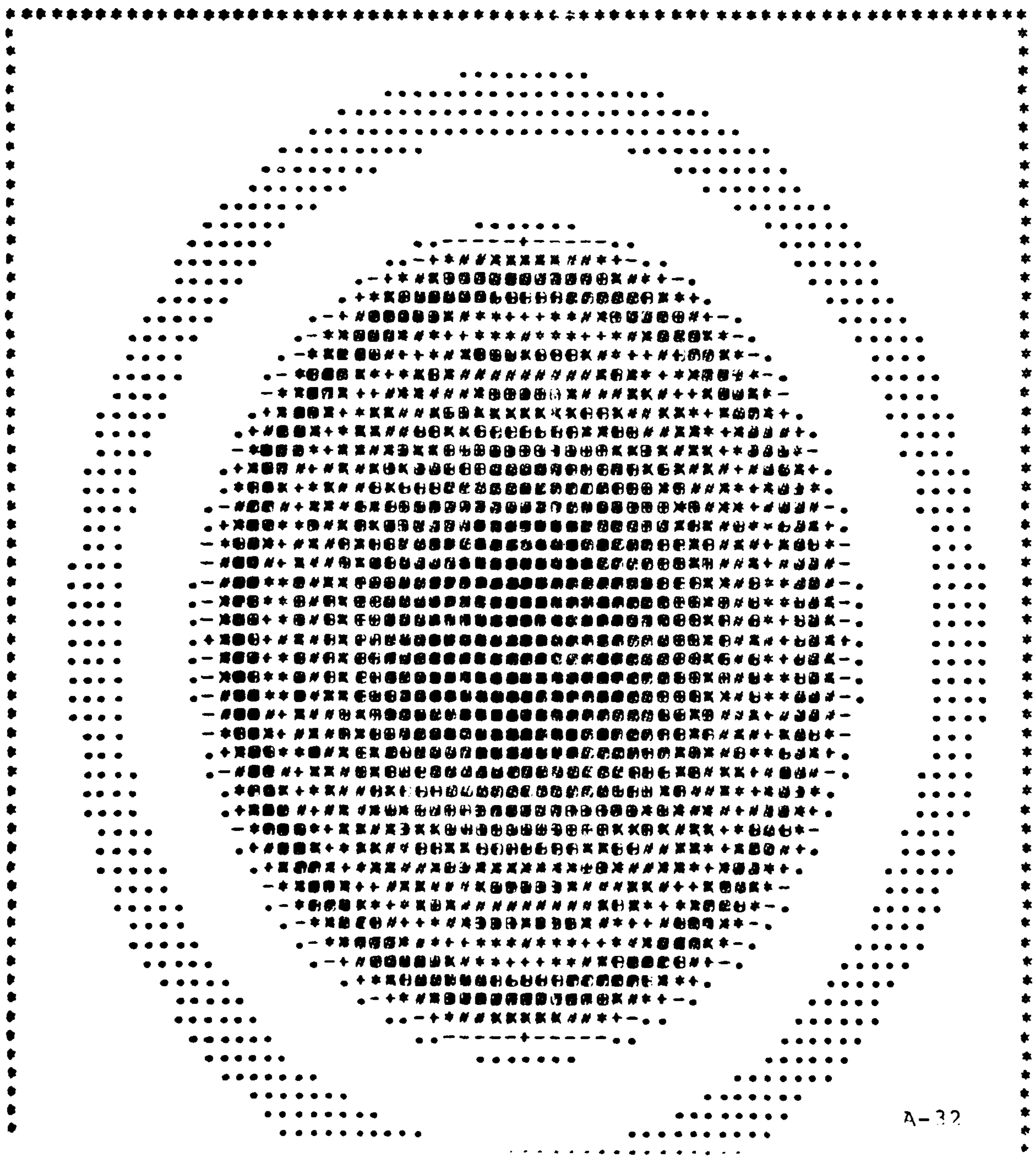
	0.597604E-02	0.105378E+00
.	0.105378E+00	0.204781E+00
-	0.204781E+00	0.304183E+00
+	0.304183E+00	0.403585E+00
*	0.403586E+00	0.502988E+00
/	0.502988E+00	0.602390E+00
X	0.602390E+00	0.701793E+00
■	0.701793E+00	0.801195E+00
■	0.801195E+00	0.900598E+00
■	0.900598E+00	0.100000E+01

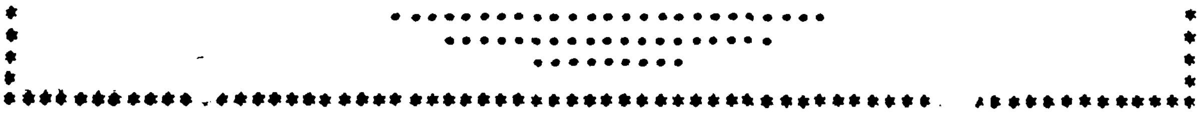
THIS IS STEP 1

SUML = 0.4859293E+00 SUMR = 0.5140707E+00

BEAM WAIST IN X AND Y DIRECTIONS IS 19.50356 19.50494 MICRONS

IRRADIAN





IRRADIAN

GREY-SCALE CHARACTERS AND RANGES

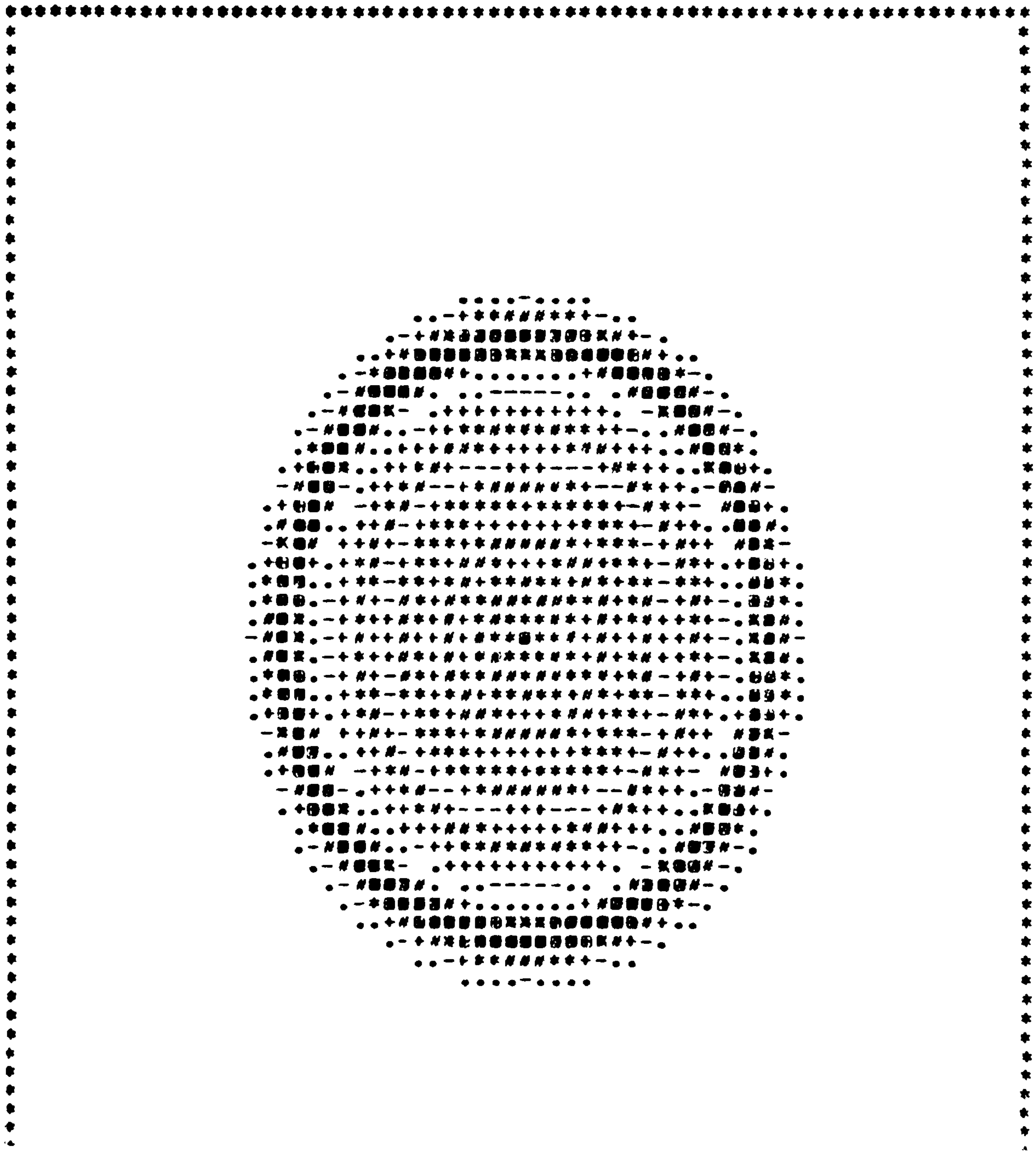
	0.585011E-02	0.105238E+00
.	0.105238E+00	0.204626E+00
-	0.204626E+00	0.304013E+00
+	0.304013E+00	0.403401F+00
*	0.403401E+00	0.502789E+00
#	0.502789E+00	0.602177E+00
[illegible]	0.602177F+00	0.701565E+00
[illegible]	0.701565E+00	0.800952E+00
[illegible]	0.800952E+00	0.900340E+00
[illegible]	0.900340E+00	0.999728E+00

THIS IS STEP 2

SUML = 0.4851605E+00 SUMR = 0.5148394F+00

BEAM WAIST IN X AND Y DIRECTIONS IS 18.72375 18.72498 MICRONS

IRRADIAN



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IRRADIAN

GREY-SCALE CHARACTERS AND RANGES

	0.323949E-02	0.211144E+00
.	0.211144E+00	0.419048E+00
-	0.419048E+00	0.626953E+00
+	0.626953E+00	0.834857E+00
*	0.834857E+00	0.104276E+01
#	0.104276E+01	0.125066E+01
X	0.125067E+01	0.145857E+01
■	0.145857E+01	0.166647E+01
■	0.166647E+01	0.187438E+01
■	0.187438E+01	0.208228E+01

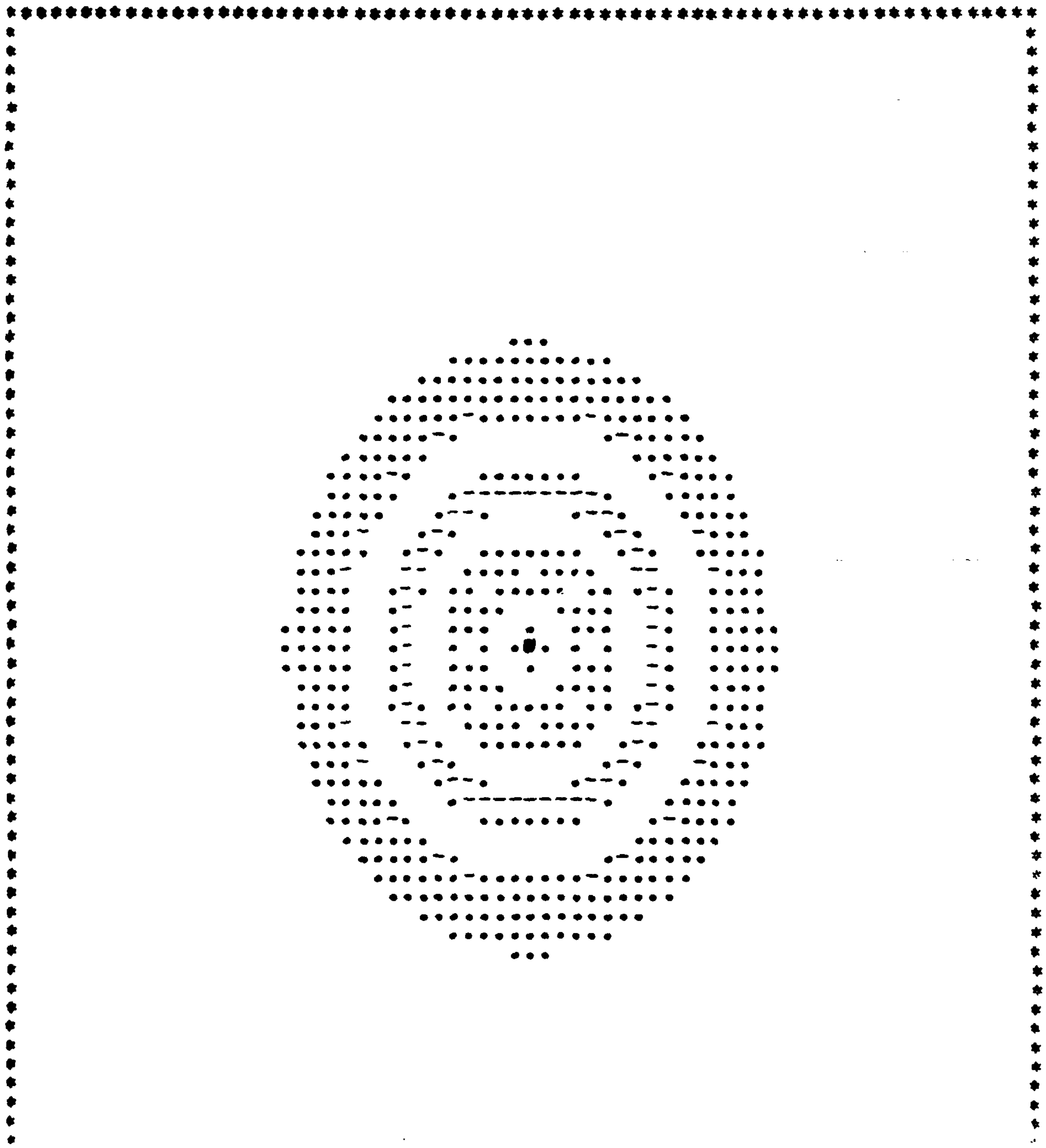
THIS IS STEP 3

SUML = 0.4817133E+00 SUMR = 0.5182866E+00

BEAM WAIST IN X AND Y DIRECTIONS IS 18.07376 18.07498 MICRONS

P-16A

IRRADIAN



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IRRADIAN

GREY-SCALE CHARACTERS AND RANGES

	0.759699E-05	0.842067E+00
.	0.842067E+00	0.168413E+01
-	0.168412E+01	0.252618E+01
+	0.252618E+01	0.336824E+01
*	0.336824E+01	0.421030E+01
#	0.421030E+01	0.505236E+01
	0.505236E+01	0.589442E+01
	0.589442E+01	0.673648E+01
	0.673648E+01	0.757854E+01
	0.757854E+01	0.842060E+01

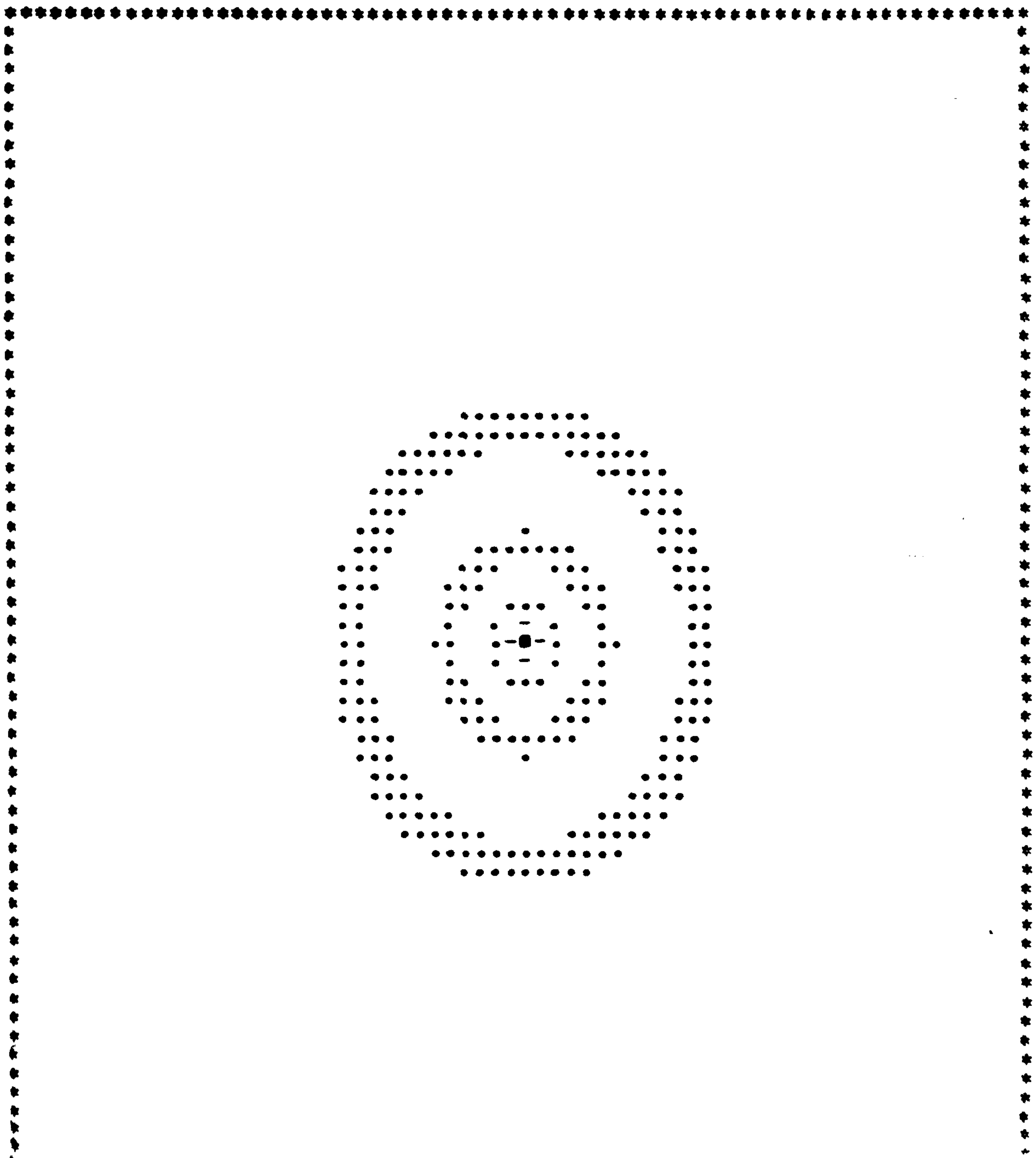
THIS IS STEP 4

SUML = 0.4754750E+00 SUMR = 0.5245249E+00

BEAM WAIST IN X AND Y DIRECTIONS IS 17.64449 17.64572 MICRONS

P-10

IRRADIAN



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  IRRADIAN

GREY-SCALE CHARACTERS AND RANGES

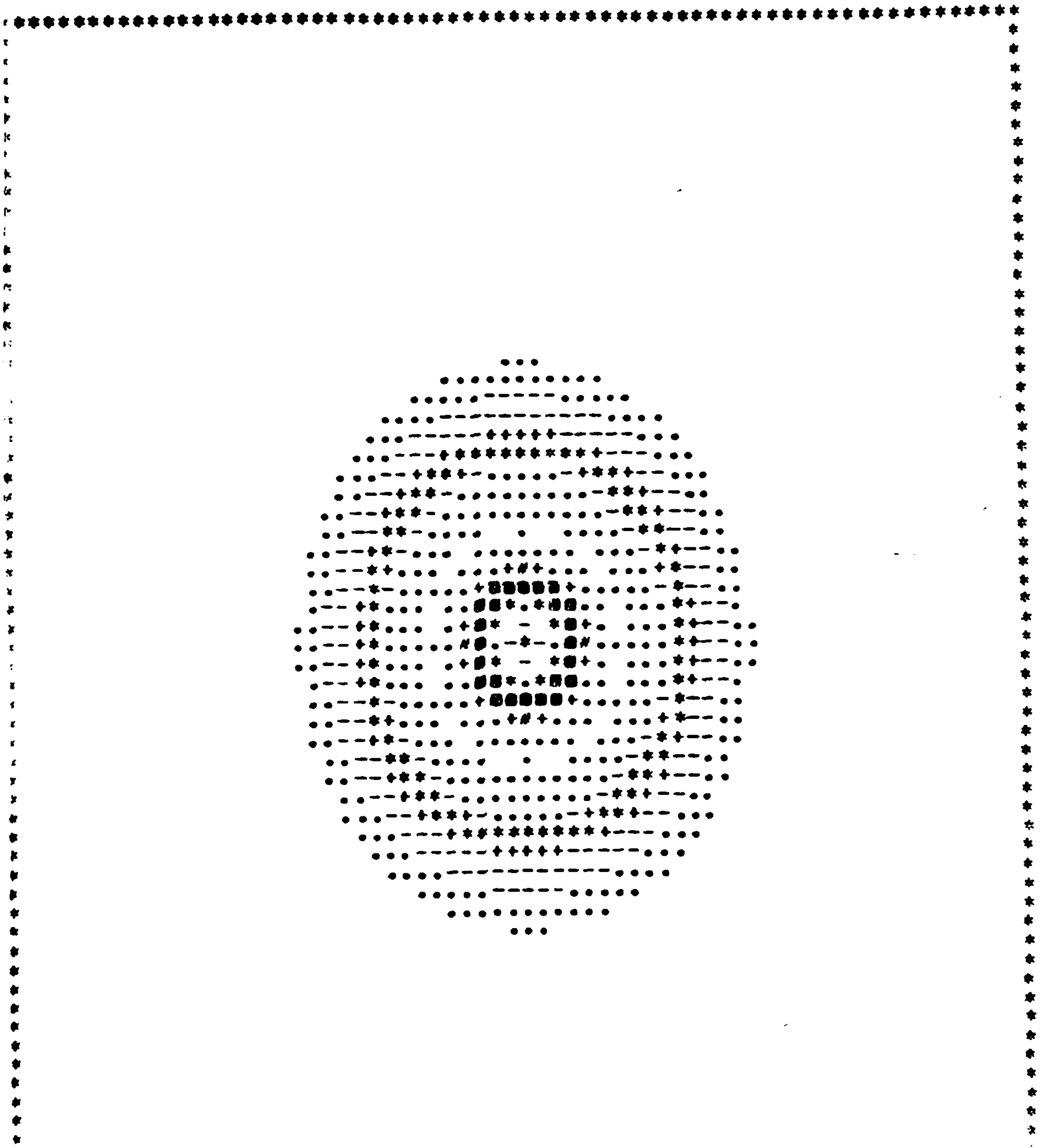
                 0.247009E-03         0.153054E+01
        .        0.153054E+01         0.306083E+01
        -        0.306083E+01         0.459112E+01
        +        0.459112E+01         0.612142E+01
        *        0.612142E+01         0.765171E+01
        #        0.765171E+01         0.918200E+01
        ¤        0.918200E+01         0.107123E+02
        ■        0.107123E+02         0.122426E+02
        ■        0.122426E+02         0.137729E+02
        ■        0.137729E+02         0.153032E+02

THIS IS STEP  5

SUML =  0.4803946E+00   SUMR =  0.5196053E+00

BEAM WAIST IN X AND Y DIRECTIONS IS     17.43616     17.43765  MICRONS
```

IRRADIAN



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  IRRADIAN

GREY-SCALE CHARACTERS AND RANGES

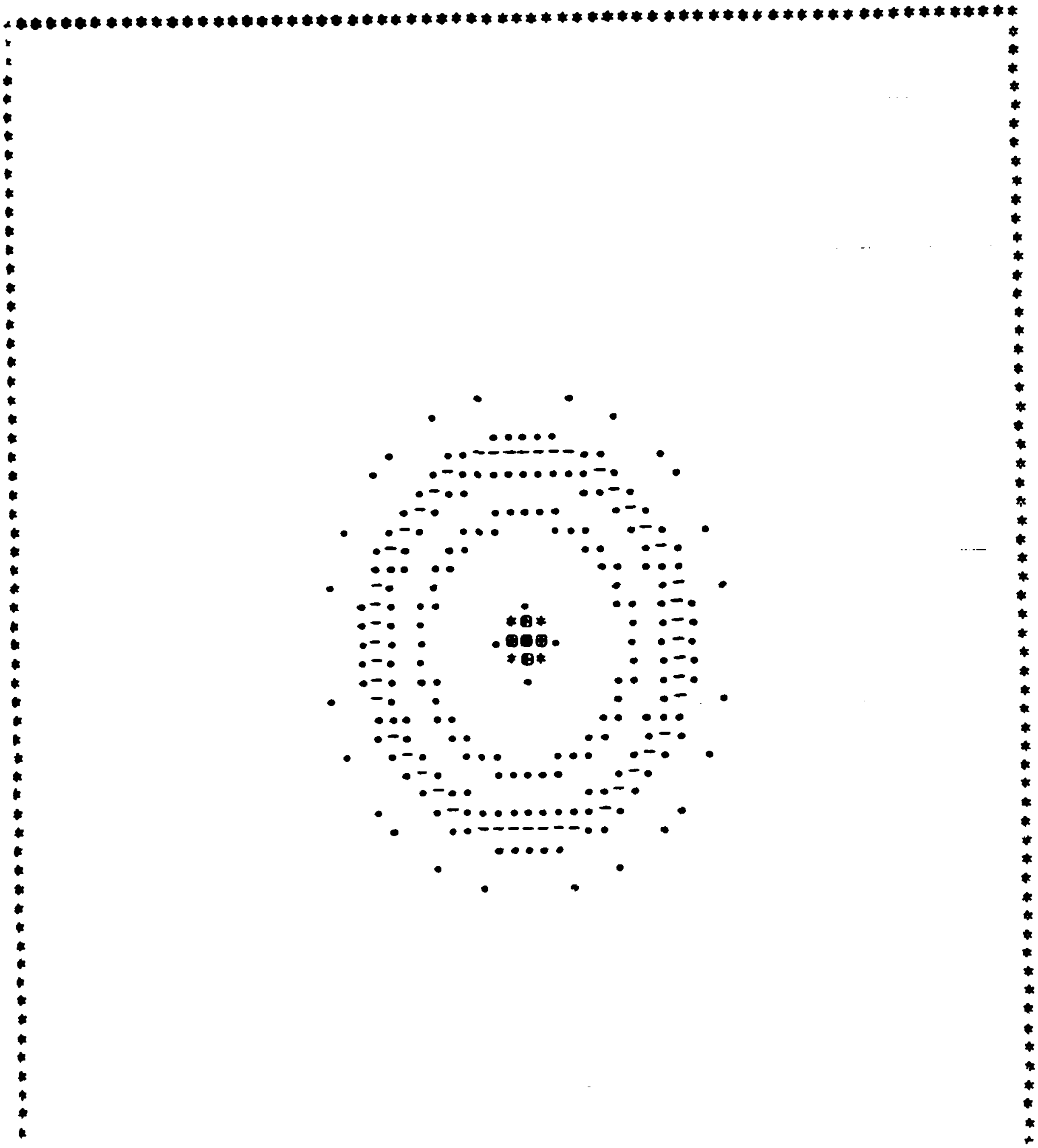
                 0.348578E-05          0.546719E+00
     .           0.546719E+00          0.109343E+01
     -           0.109343E+01          0.164015E+01
     +           0.164015E+01          0.218686E+01
     *           0.218686E+01          0.273358E+01
     #           0.273358E+01          0.328029E+01
     ■           0.328029E+01          0.382701E+01
     ■           0.382701E+01          0.437372E+01
     ■           0.437373E+01          0.492044E+01
     ■           0.492044E+01          0.546716E+01

THIS IS STEP  6

SUML =   0.4704280E+00    SUMR =   0.5295719E+00

BEAM WAIST IN X AND Y DIRECTIONS IS     17.47115     17.47259   MICRONS
```

IRRADIAN



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**********   ****************************************************   *************

  IRRADIAN

GREY-SCALE CHARACTERS AND RANGES

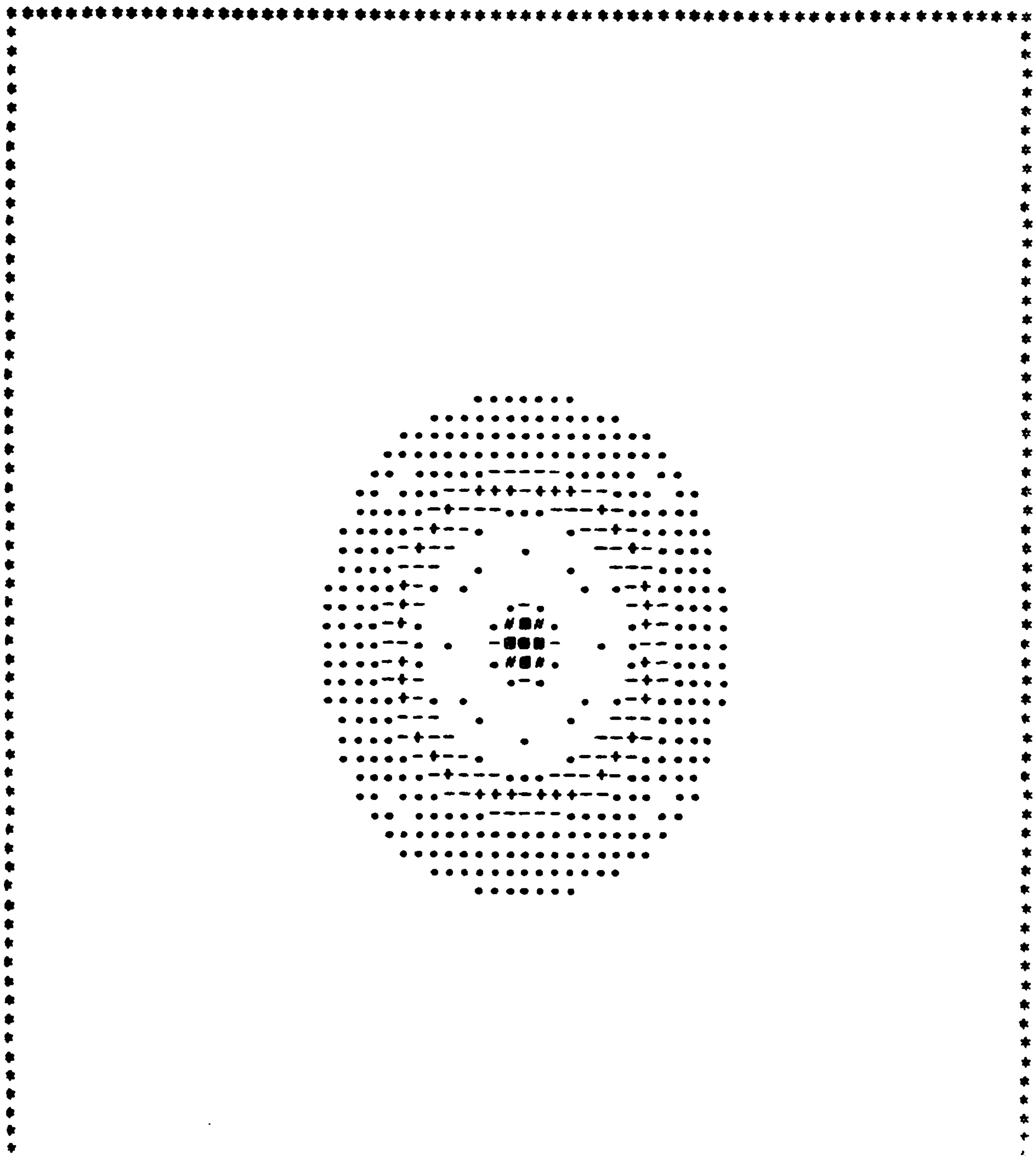
                0.341598E-04          0.146743E+01
     .          0.146743E+01          0.293483E+01
     -          0.293483E+01          0.440223E+01
     +          0.440223E+01          0.586963E+01
     *          0.586963E+01          0.733703E+01
     #          0.733703E+01          0.880443E+01
     X          0.880443E+01          0.102718E+02
     ■          0.102718E+02          0.117392E+02
     ■          0.117392E+02          0.132066E+02
     ■          0.132066E+02          0.146740E+02

THIS IS STEP  7

SUML =  0.4736281E+00   SUMR =  0.5263718E+00

BEAM WAIST IN X AND Y DIRECTIONS IS    17.75745    17.75934  MICRONS
```

IRRADIAN



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IRRADIAN

GREY-SCALE CHARACTERS AND RANGES

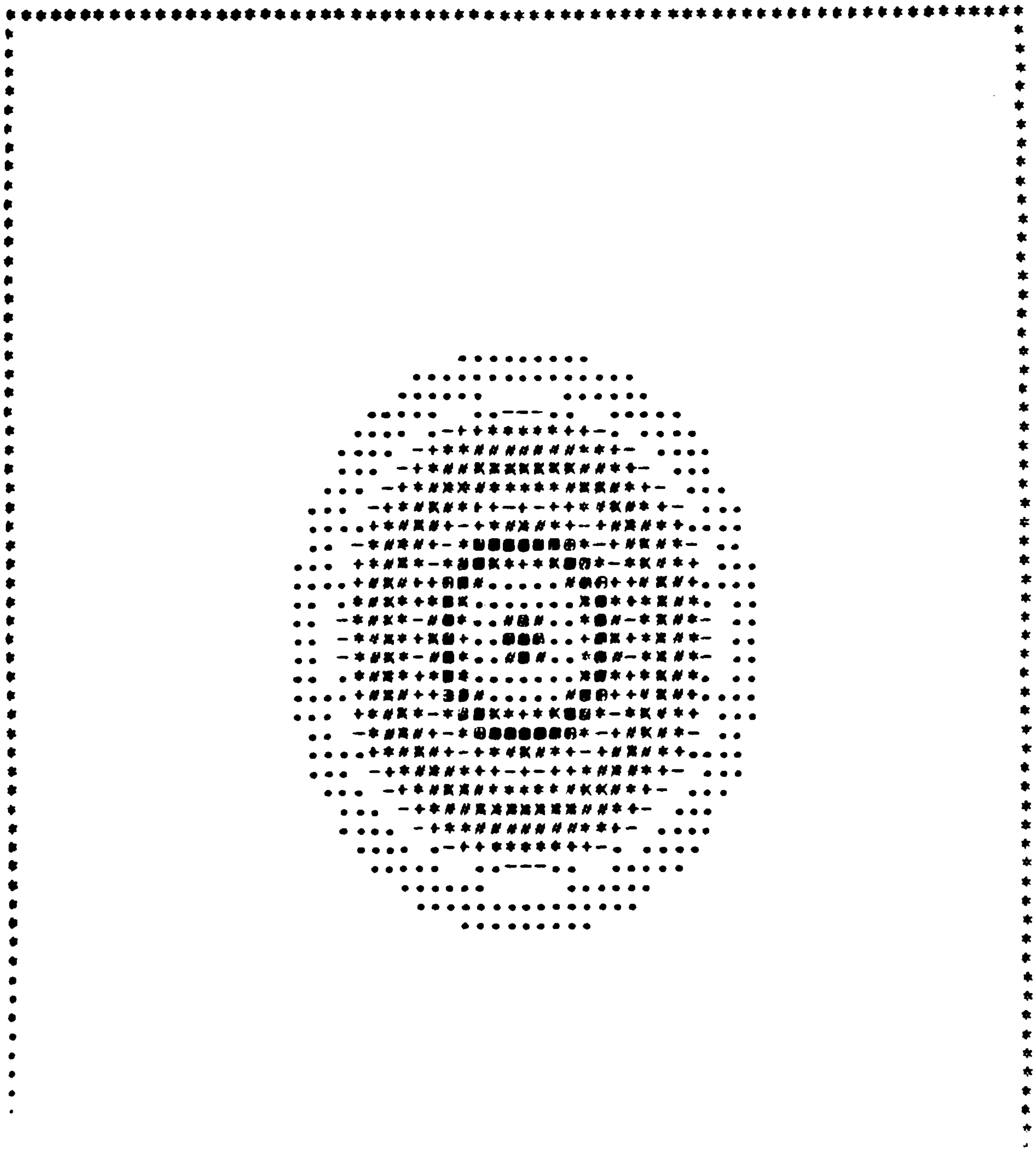
	0.349578E-03	0.996981E+00
.	0.996981E+00	0.199361E+01
-	0.199361E+01	0.299024E+01
+	0.299024E+01	0.398687E+01
*	0.398688E+C1	0.498351E+01
#	0.498351E+01	0.598014E+01
	0.598014E+01	0.697677E+01
	0.697677E+01	0.797340E+01
	0.797340F+01	0.897003E+01
	0.897003F+01	0.996667E+01

THIS IS STEP 8

SUML = 0.4800833E+00 SUMR = 0.5199167E+00

BEAM WAIST IN X AND Y DIRECTIONS IS 18.20370 18.20607 MICRONS

IRRADIAN



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IRRADIAN

GREY-SCALE CHARACTERS AND RANGES

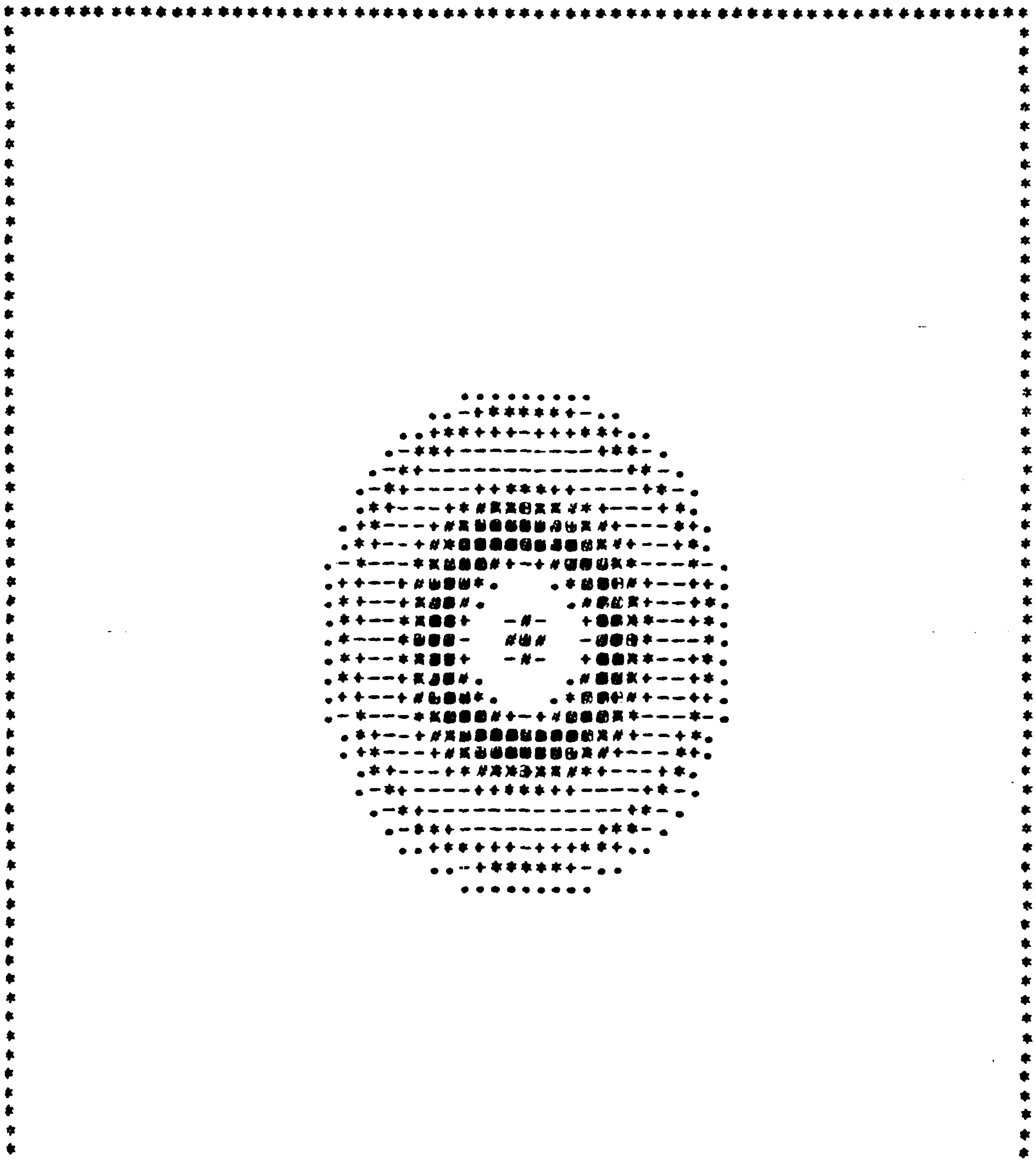
	0.213262E-03	0.358114E+00
.	0.358113E+00	0.716014E+00
-	0.716014E+00	0.107391E+01
+	0.107391E+01	0.143181E+01
*	0.143181E+01	0.178971E+01
#	0.178971E+01	0.214761E+01
X	0.214761E+01	0.250551E+01
■	0.250551E+01	0.286341E+01
■	0.286341E+01	0.322131E+01
■	0.322132E+01	0.357922E+01

THIS IS STEP 9

SUML = 0.4812048E+00 SUMR = 0.5187951E+00

BEAM WAIST IN X AND Y DIRECTIONS IS 18.54669 18.54912 MICRONS

IRRADIAN



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IRRADIAN

GREY-SCALE CHARACTERS AND RANGES

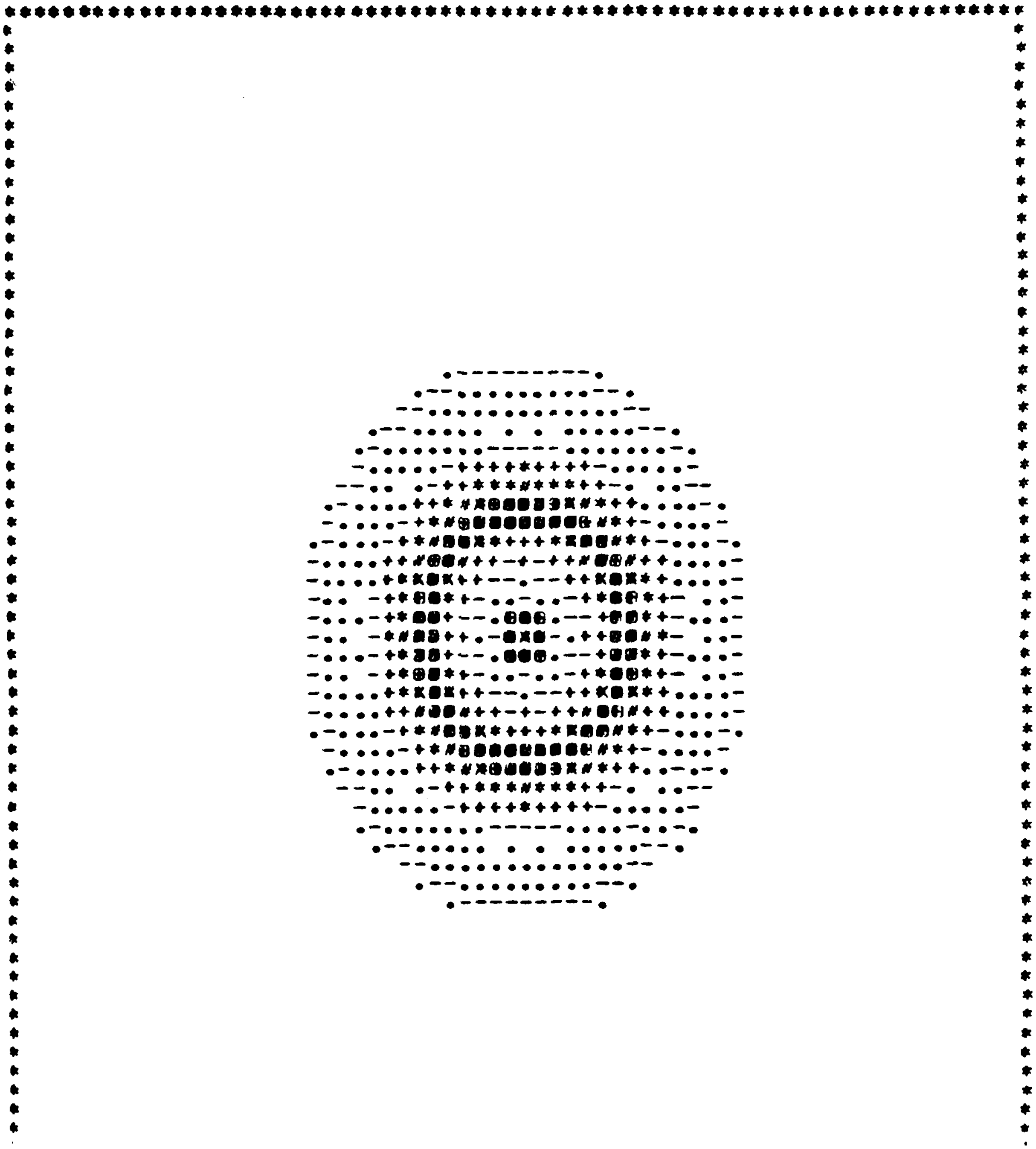
	0.753595E-04	0.379830E+00
.	0.379830E+00	0.759584E+00
-	0.759584E+00	0.113934E+01
+	0.113934E+01	0.151909E+01
*	0.151909E+01	0.189885E+01
#	0.189885E+01	0.227860E+01
■	0.227860E+01	0.265836E+01
■	0.265836E+01	0.303811E+01
■	0.303811E+01	0.341786E+01
■	0.341787E+01	0.379762E+01

THIS IS STEP 10

SUML = 0.4789906E+00 SUMR = 0.5210093E+00

BEAM WAIST IN X AND Y DIRECTIONS IS 18.63527 18.63782 MICRONS

IRRADIAN



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IRRADIAN

GREY-SCALE CHARACTERS AND RANGES

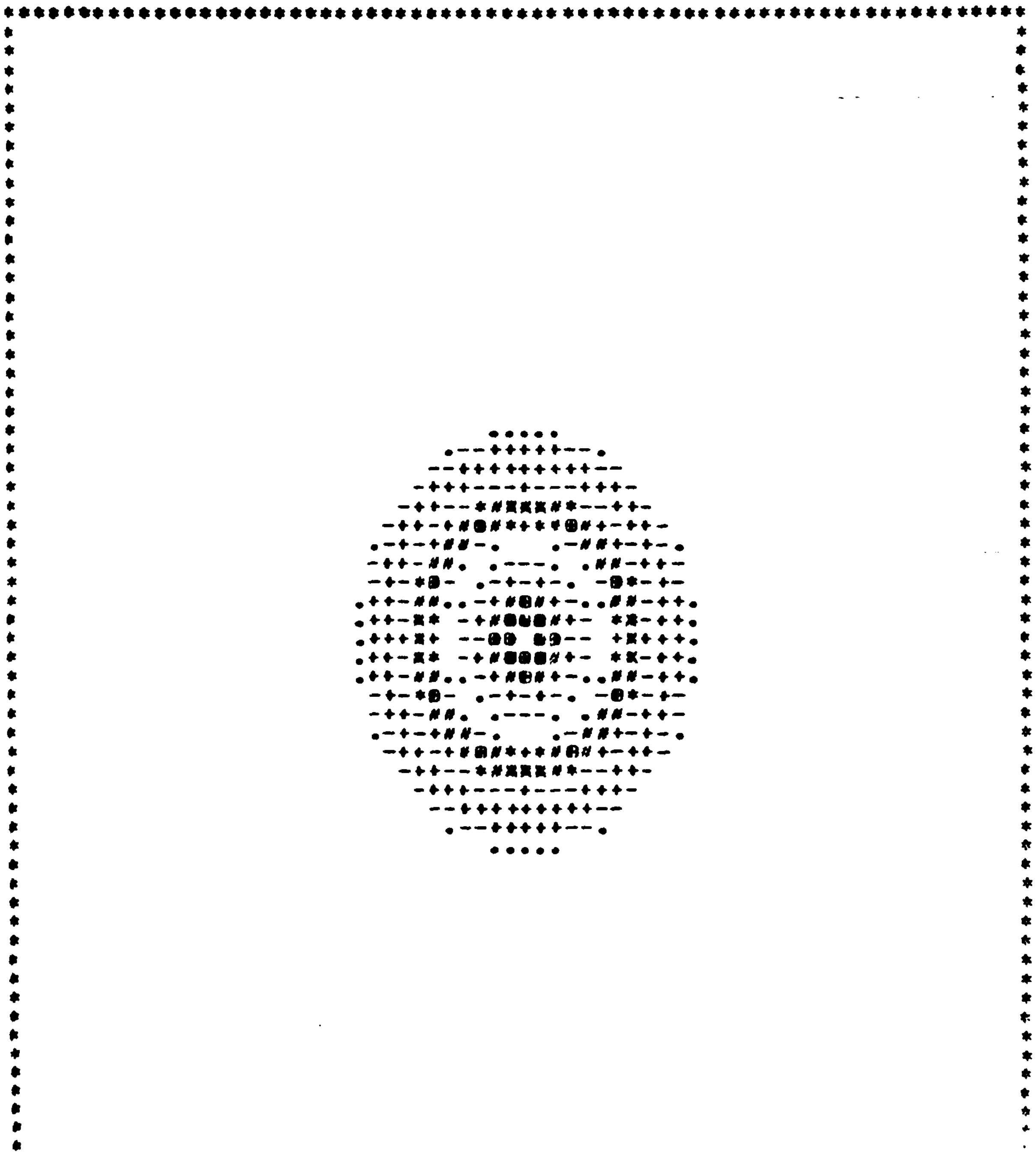
	0.103213E-03	0.410842E+00
.	0.410842E+00	0.821581E+00
-	0.821582E+00	0.123232E+01
+	0.123232E+01	0.164306E+01
*	0.164306E+01	0.205380E+01
#	0.205380E+01	0.246454E+01
X	0.246454E+01	0.287528E+01
■	0.287528E+01	0.328602E+01
■	0.328602E+01	0.369676E+01
■	0.369676E+01	0.410749E+01

THIS IS STEP 11

SUML = 0.4775044E+00 SUMR = 0.5224955E+00

BEAM WAIST IN X AND Y DIRECTIONS IS 18.77403 18.77573 MICRONS

IRRADIAN



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IRRADIAN

GREY-SCALE CHARACTERS AND RANGES

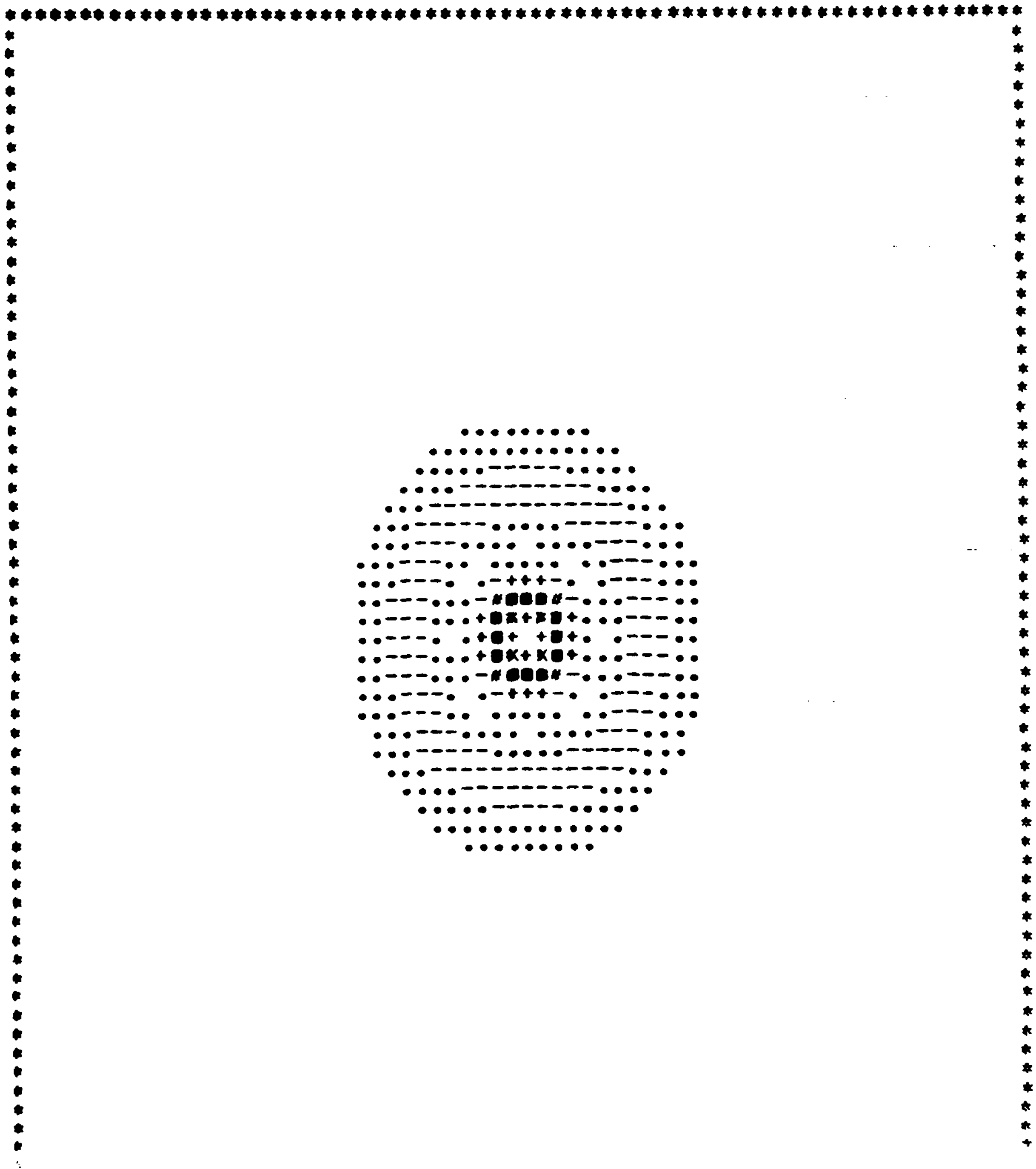
	0.373785E-04	0.594157E+00
.	0.594157E+00	0.118828E+01
-	0.118828E+01	0.178239E+01
+	0.178239E+01	0.237651E+01
*	0.237651E+01	0.297063E+01
#	0.297063E+01	0.356475E+01
■	0.356475E+01	0.415887E+01
●	0.415887E+01	0.475299E+01
■	0.475299E+01	0.534711E+01
●	0.534711E+01	0.594123E+01

THIS IS STEP 12

SUML = 0.4750217E+00   SUMR = 0.5249783E+00

BEAM WAIST IN X AND Y DIRECTIONS IS   18.92630   18.92923 MICRONS

IRRADIAN



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  IRRADIAN

GREY-SCALE CHARACTERS AND RANGES

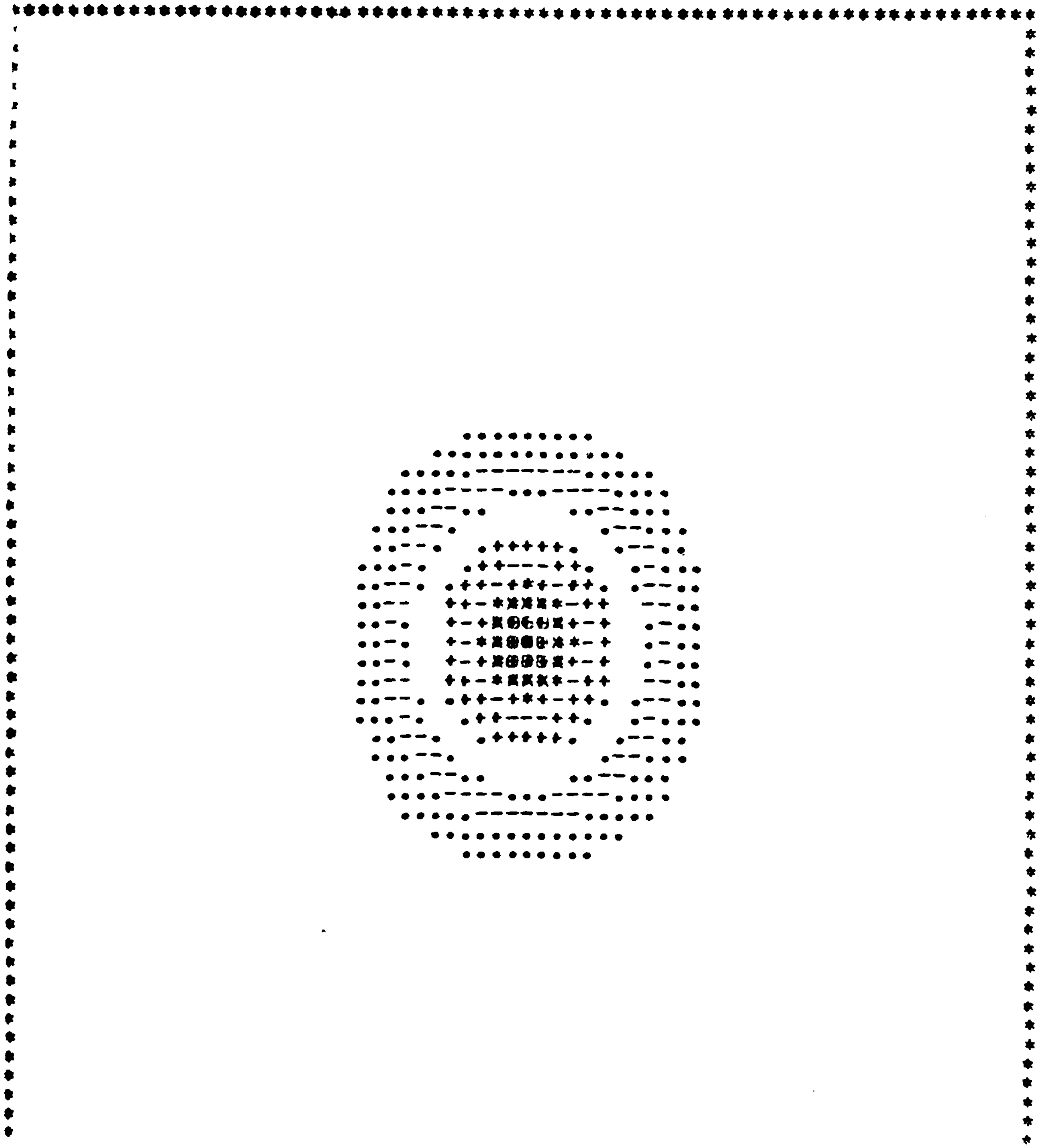
              0.126287E-04          0.898516E+00
     .        0.898516E+00          0.179702E+01
     -        0.179702E+01          0.269552E+01
     +        0.269552E+01          0.359403E+01
     *        0.359403E+01          0.449253E+01
     #        0.449253E+01          0.539103E+01
     ■        0.539103E+01          0.628954E+01
     ■        0.628954E+01          0.718804E+01
     ■        0.718804E+01          0.808654E+01
     ■        0.808654E+01          0.898505E+01

THIS IS STEP 13

SUML =   0.4702227E+00    SUMR =   0.5297772E+00

BEAM WAIST IN X AND Y DIRECTIONS IS     18.73090     18.73331   MICRONS
```

IRRADIAN



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  IRRADIAN

GREY-SCALE CHARACTERS AND RANGES

                0.703742E-04          0.848021E+00
     .          0.848021E+00          0.169597E+01
     -          0.169597E+01          0.254392E+01
     +          0.254392E+01          0.339187E+01
     *          0.339187E+01          0.423982E+01
     #          0.423982E+01          0.508778E+01
     ■          0.508778E+01          0.593573E+01
     ■          0.593573E+01          0.678368E+01
     ■          0.678368E+01          0.763163E+01
     ●          0.763163E+01          0.847958E+01

THIS IS STEP 14

SUML =  0.4651438E+00   SUMR =  0.5348561E+00

BEAM WAIST IN X AND Y DIRECTIONS IS    18.77950    18.78253  MICRONS
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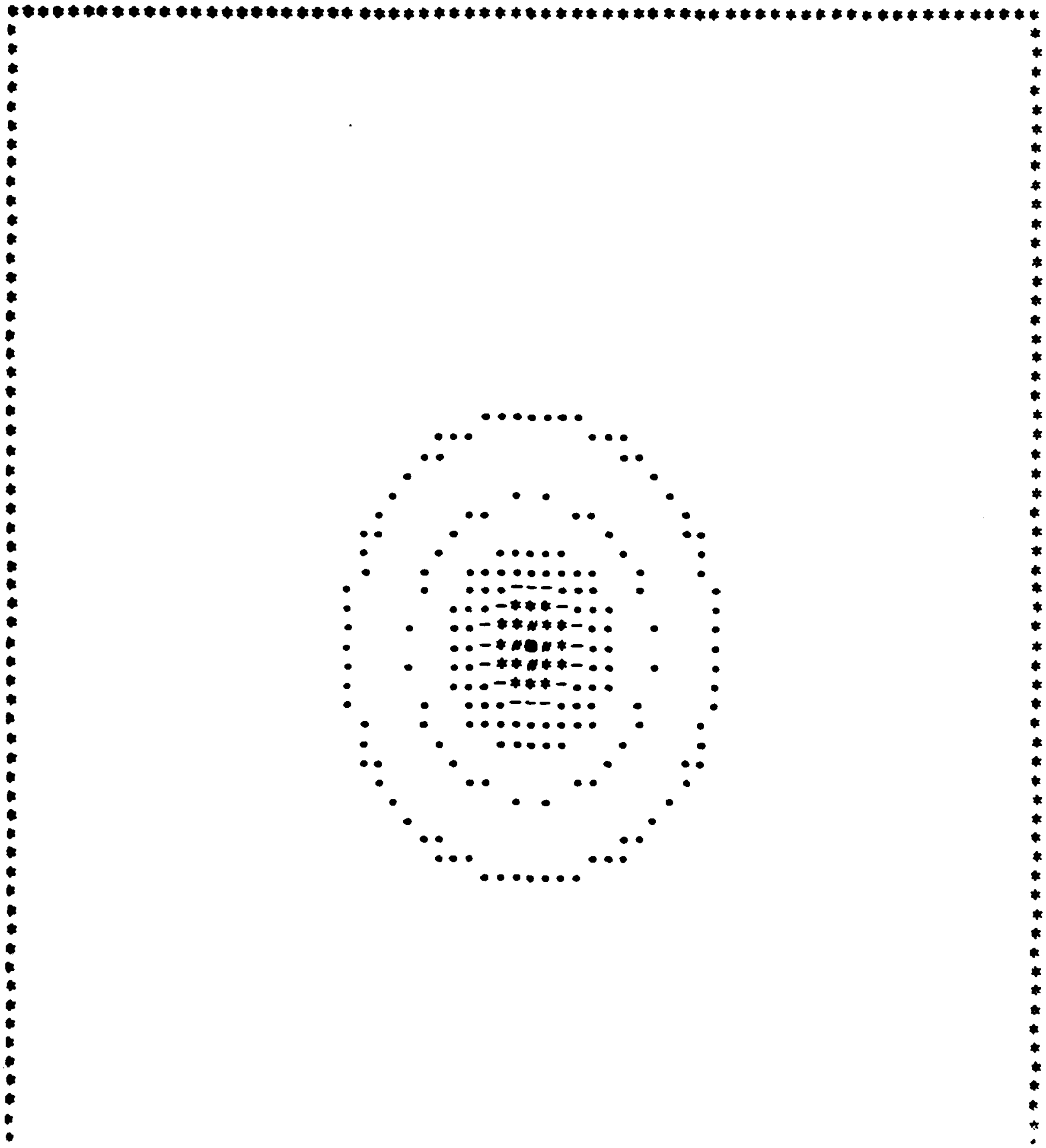
IRRADIAN



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IRRADIAN

GREY-SCALE CHARACTERS AND RANGES

	0.244114E-03	0.155652E+01
.	0.155652E+01	0.311279E+01
-	0.311279E+01	0.466906E+01
+	0.466906E+01	0.622533E+01
*	0.622534E+01	0.778161E+01
#	0.778161E+01	0.933788E+01
X	0.933788E+01	0.108942E+02
■	0.108942E+02	0.124504E+02
■	0.124504E+02	0.140067E+02
■	0.140067E+02	0.155630E+02

THIS IS STEP 15

SUML = 0.4690364E+00   SUMR = 0.5309635E+00

BEAM WAIST IN X AND Y DIRECTIONS IS   18.87981   18.88269   MICRONS

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OCT 80 C YEH F19628-80-C-0053
UNCLASSIFIED EM-F-02 RADC-TR-80-332 NL

2 of 2

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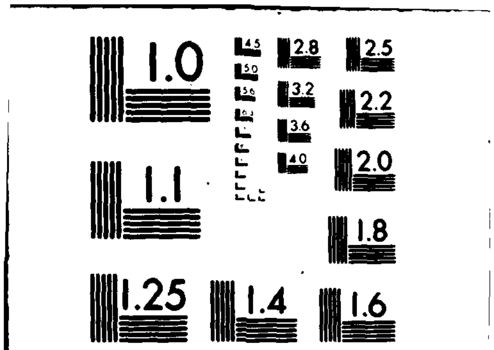
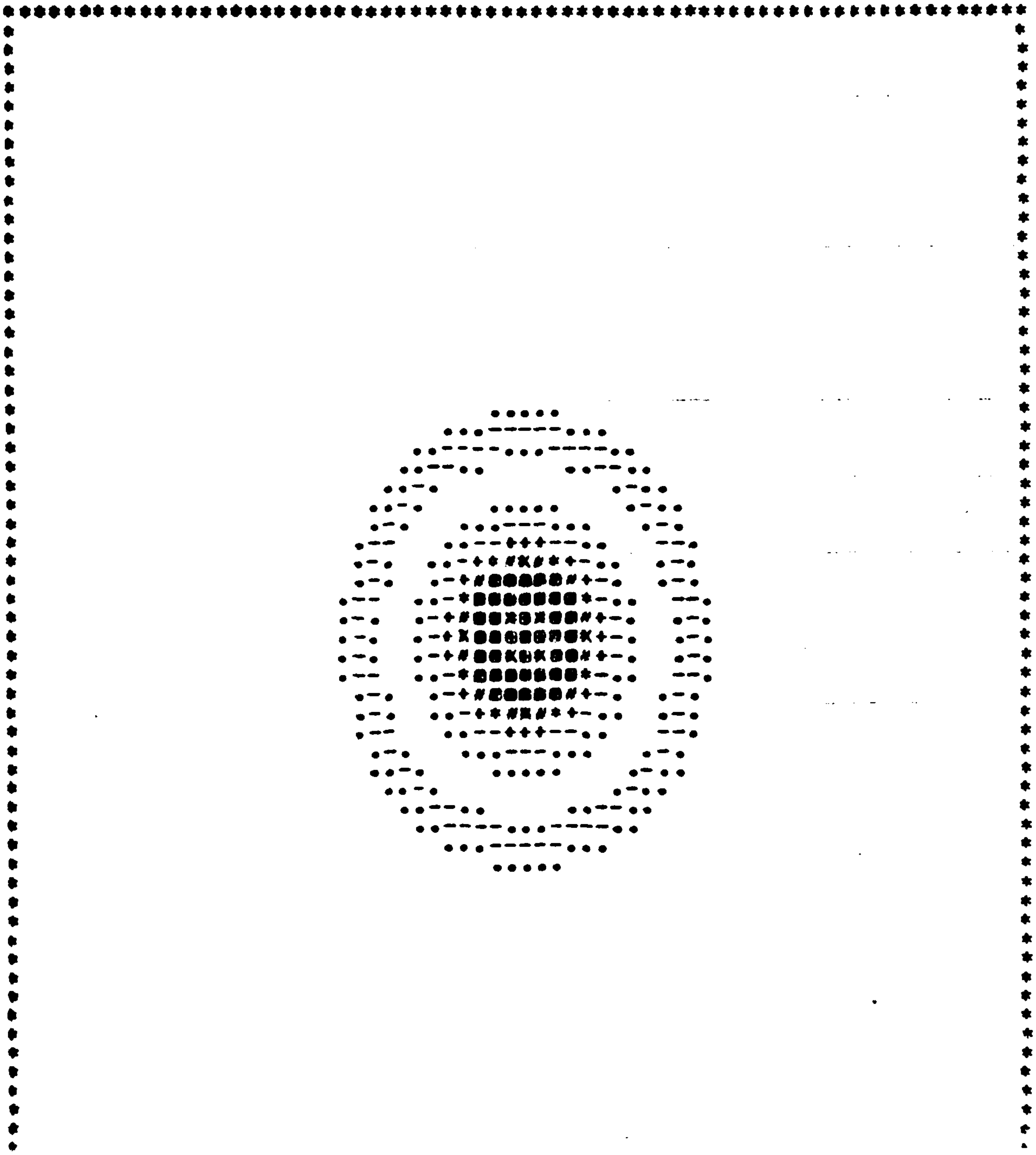


MICROCOPY RESOLUTION TEST CHART

101

IRRADIAN



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IRRADIAN

GREY-SCALE CHARACTERS AND RANGES

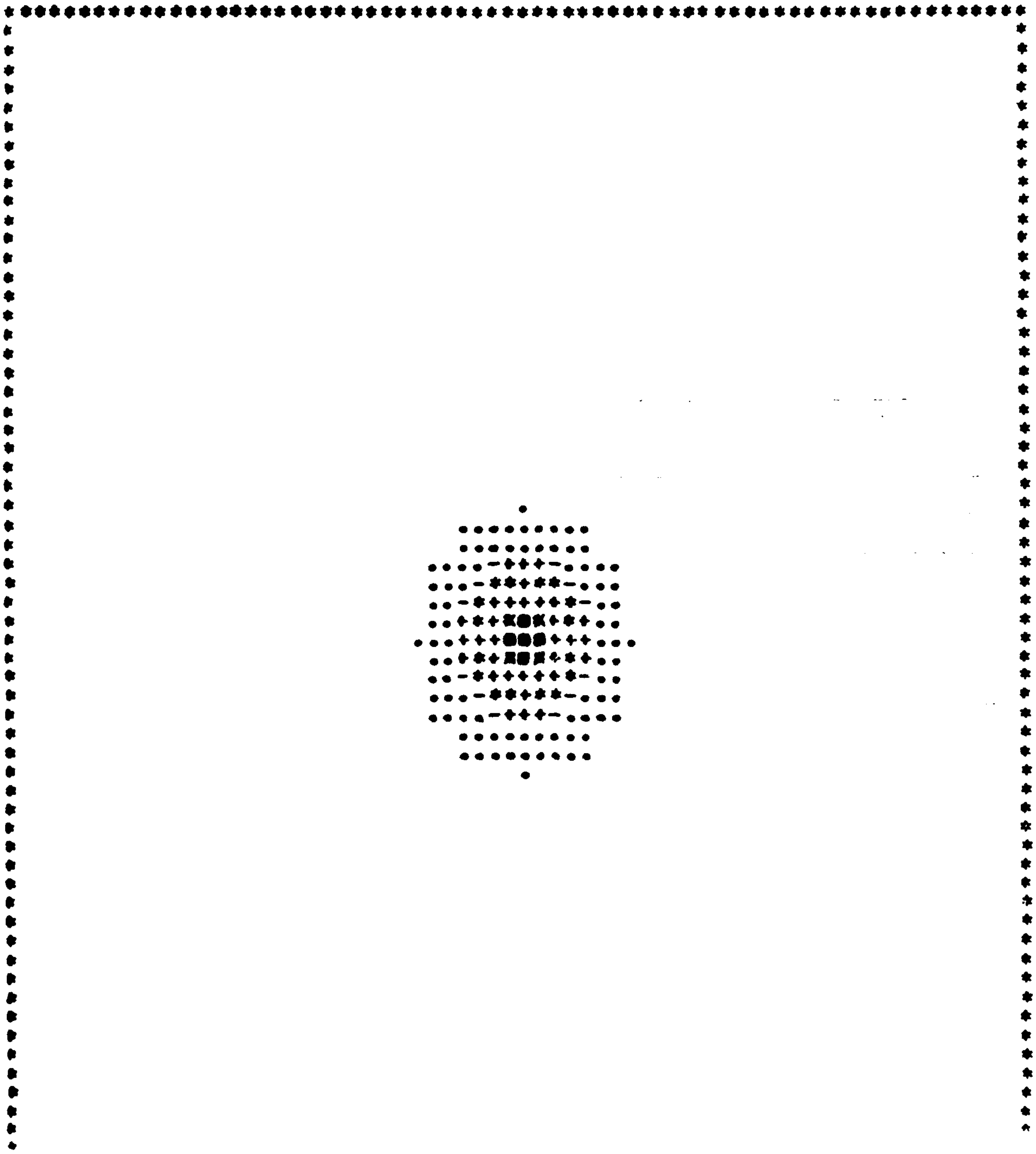
	0.246905E-03	0.697666E+00
.	0.697666E+00	0.139509E+01
-	0.139508E+01	0.209250E+01
+	0.209250E+01	0.278992E+01
*	0.278992E+01	0.348734E+01
#	0.348734E+01	0.418476E+01
■	0.418476E+01	0.488218E+01
■	0.488218E+01	0.557960E+01
■	0.557960E+01	0.627702E+01
■	0.627702E+01	0.697444E+01

THIS IS STEP 16

SUML = 0.4632549E+00   SUMR = 0.5367450E+00

BEAM WAIST IN X AND Y DIRECTIONS IS   19.10669   19.10956   MICRONS

IRRADIAN



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  IRRADIAN

GREY-SCALE CHARACTERS AND RANGES

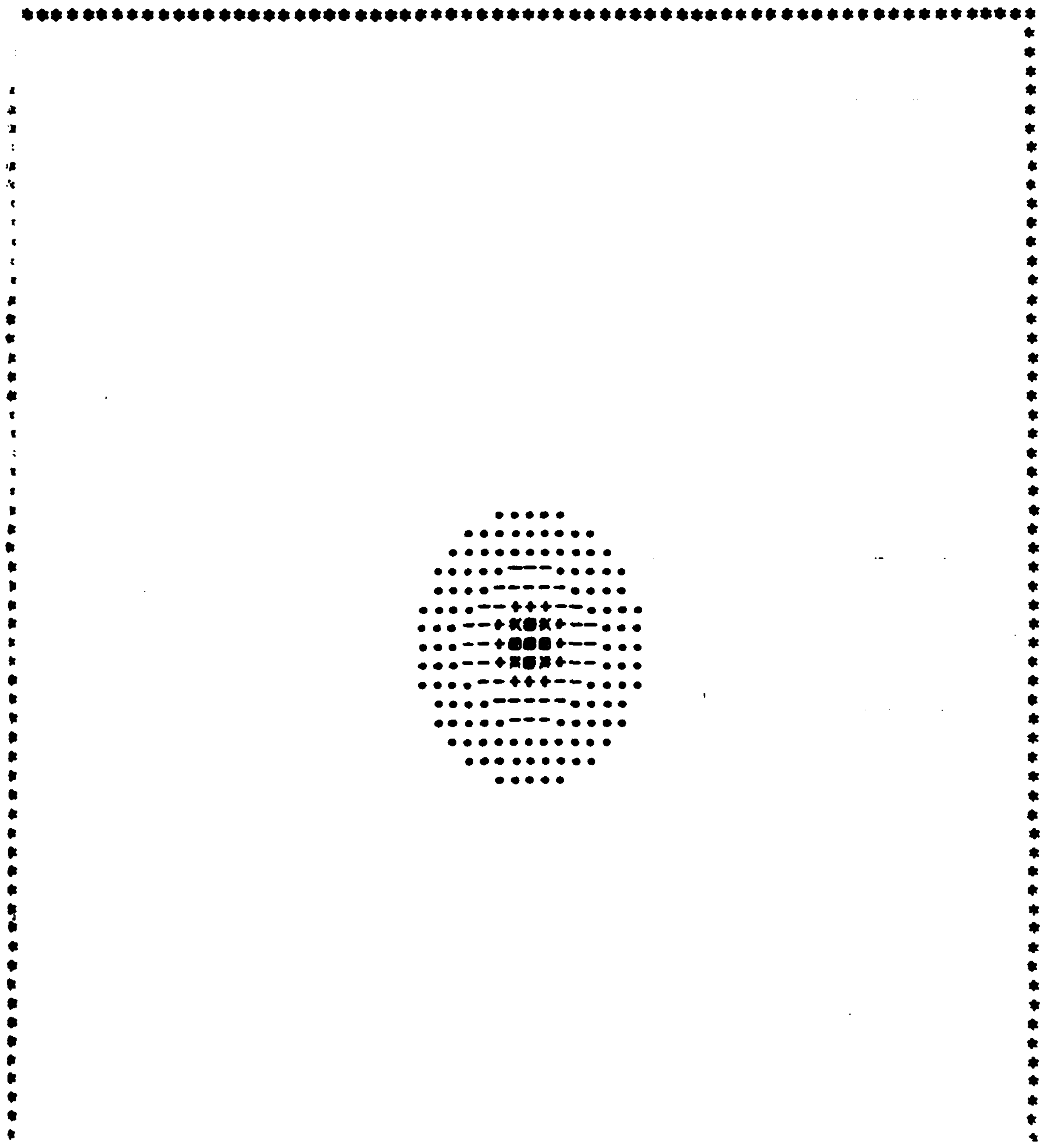
                0.911394E-03          0.131676E+01
     .          0.131676E+01          0.263261E+01
     -          0.263261E+01          0.394845E+01
     +          0.394845E+01          0.526430E+01
     *          0.526430E+01          0.658015E+01
     #          0.658015E+01          0.789600E+01
     X          0.789600E+01          0.921185E+01
     ■          0.921185E+01          0.105277E+02
     ■          0.105277E+02          0.118435E+02
     ■          0.118435E+02          0.131594E+02

THIS IS STEP 17

SUML =  0.4618073E+00   SUMR =  0.5381926E+00

BEAM WAIST IN X AND Y DIRECTIONS IS     19.16985     19.17290   MICRONS
```

IRRADIAN



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IRRADIAN

GREY-SCALE CHARACTERS AND RANGES

	0.192583E-04	0.159542E+01
.	0.159542E+01	0.319081E+01
-	0.319081E+01	0.478621E+01
+	0.478621E+01	0.638161E+01
*	0.638161E+01	0.797700E+01
#	0.797700E+01	0.957240E+01
	0.957240E+01	0.111678E+02
	0.111678E+02	0.127632E+02
	0.127632E+02	0.143586E+02
	0.143586E+02	0.159540E+02

THIS IS STEP 18

SUML = 0.4730968E+00 SUMR = 0.5269032E+00

BEAM WAIST IN X AND Y DIRECTIONS IS 19.34006 19.34309 MICRONS

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RADC plans and executes research, development, test and selected acquisition programs in support of Command, Control Communications and Intelligence (C^3I) activities. Technical and engineering support within areas of technical competence is provided to ESD Program Offices (POs) and other ESD elements. The principal technical mission areas are communications, electromagnetic guidance and control, surveillance of ground and aerospace objects, intelligence data collection and handling, information system technology, ionospheric propagation, solid state sciences, microwave physics and electronic reliability, maintainability and compatibility.

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